Final report

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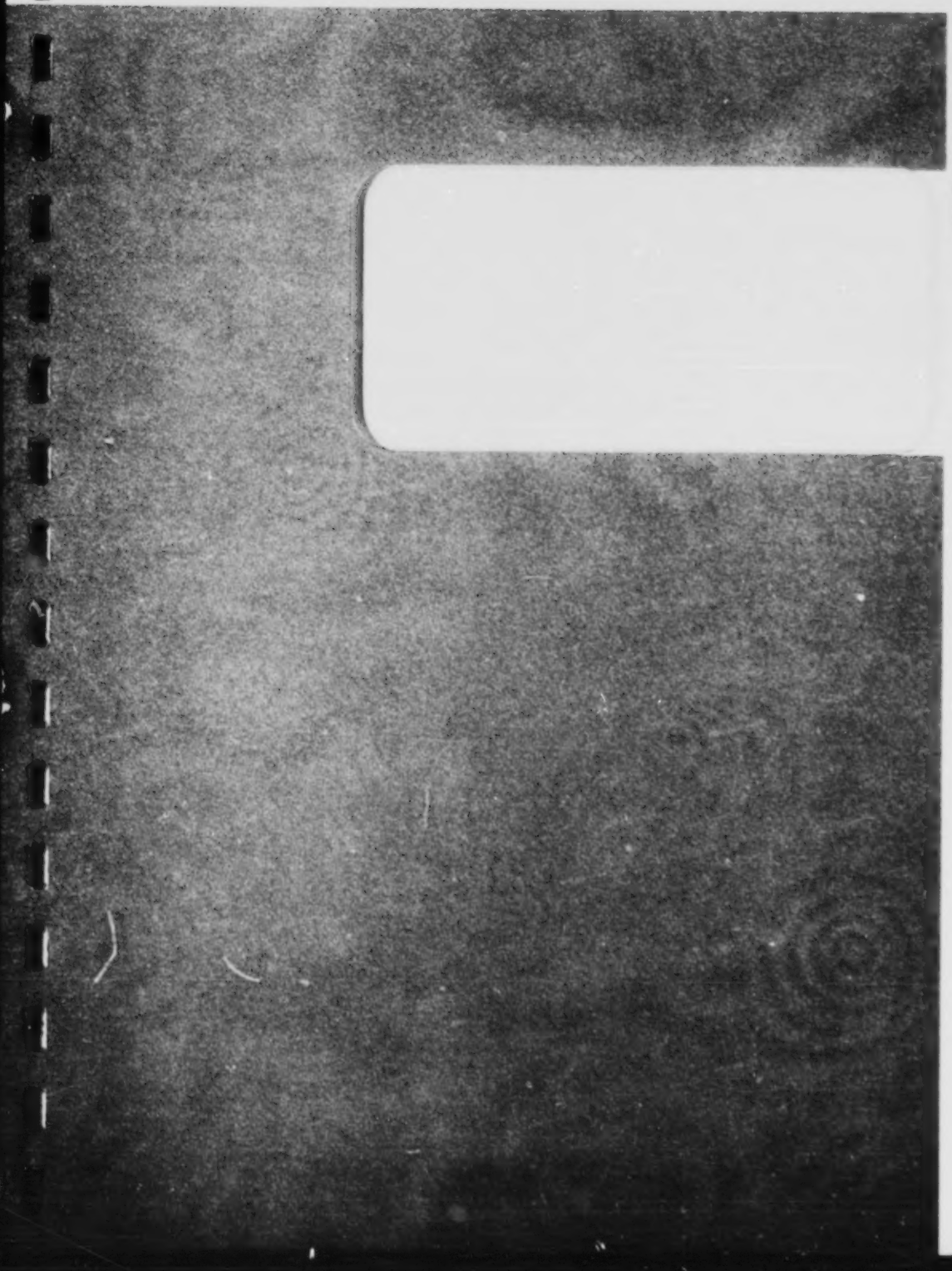

Gartner
Lee
Associates
Limited

SITE ASSESSMENT
PHASE 4B:
GEOLOGY, HYDROGEOLOGY AND GEOTECHNICS - HYDROGEOLOGIC INPUT TO LANDFILL DESIGN

Prepared for
The Ontario Waste Management Corporation

Submitted By

Gartner Lee Limited

September, 1987

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Professional Services in Environmental Management

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November 9, 1987 GLL 87-562

Mr. J.G. Micak
Manager, Environmental Projects
Ontario Waste Management Corporation
2 Bloor Street West
11th Floor
Toronto, Ontario
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Attention: Mr. D.F. Chollak
Environmental Planner

Dear Sirs:

Re: Site Assessment Phase 4B: Geology, Hydrogeology and Geotechnics - Hydrologic Input to Landfill Design

We are pleased to provide you with our above noted report. This report is one of six Phase 4B comparison reports describing baseline conditions, hydrogeologic inputs to landfill design, geotechnical inputs to facilities design, potential impacts of the landfill on ground water, potential impacts of the central operating area on ground water and ground water management strategies.

We thank you for this opportunity to be of service. Should you have any questions please do not hesitate to call.

Yours very truly,

GARTNER LEE LIMITED

E.G. Anderson, P.Eng.,
Consulting Hydrogeologist,
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UNITS AND ABBREVIATIONS

The units employed in this report are those of the SI metric system. The basic units are:

Property	SI Unit	SI Symbol
mass	kilogram	kg
length	metre	m
time	second	s
force	newton	N

The application of these units is described in Freeze and Cherry (1979, Appendix I, pp. 526-530).

In some instances, other metric units have been used. These include:

Property	Unit	Symbol
length	millimetre	mm
time	year	a

All abbreviations are identified where they first occur in the text.

1.0 INTRODUCTION

1.1 BACKGROUND

This report documents a portion of the geoscience studies (which incorporates geology, hydrogeology and geotechnics) carried out as part of Phase 4B of the Ontario Waste Management Corporation's (OWMC) Facilities Development Process. Phase 4B involves detailed assessments of the Preferred Site and surrounding area based on several disciplines, including the geosciences. The Preferred Site and immediate vicinity are illustrated in Figure 1-1.

The specific objectives of Phase 4B are to:

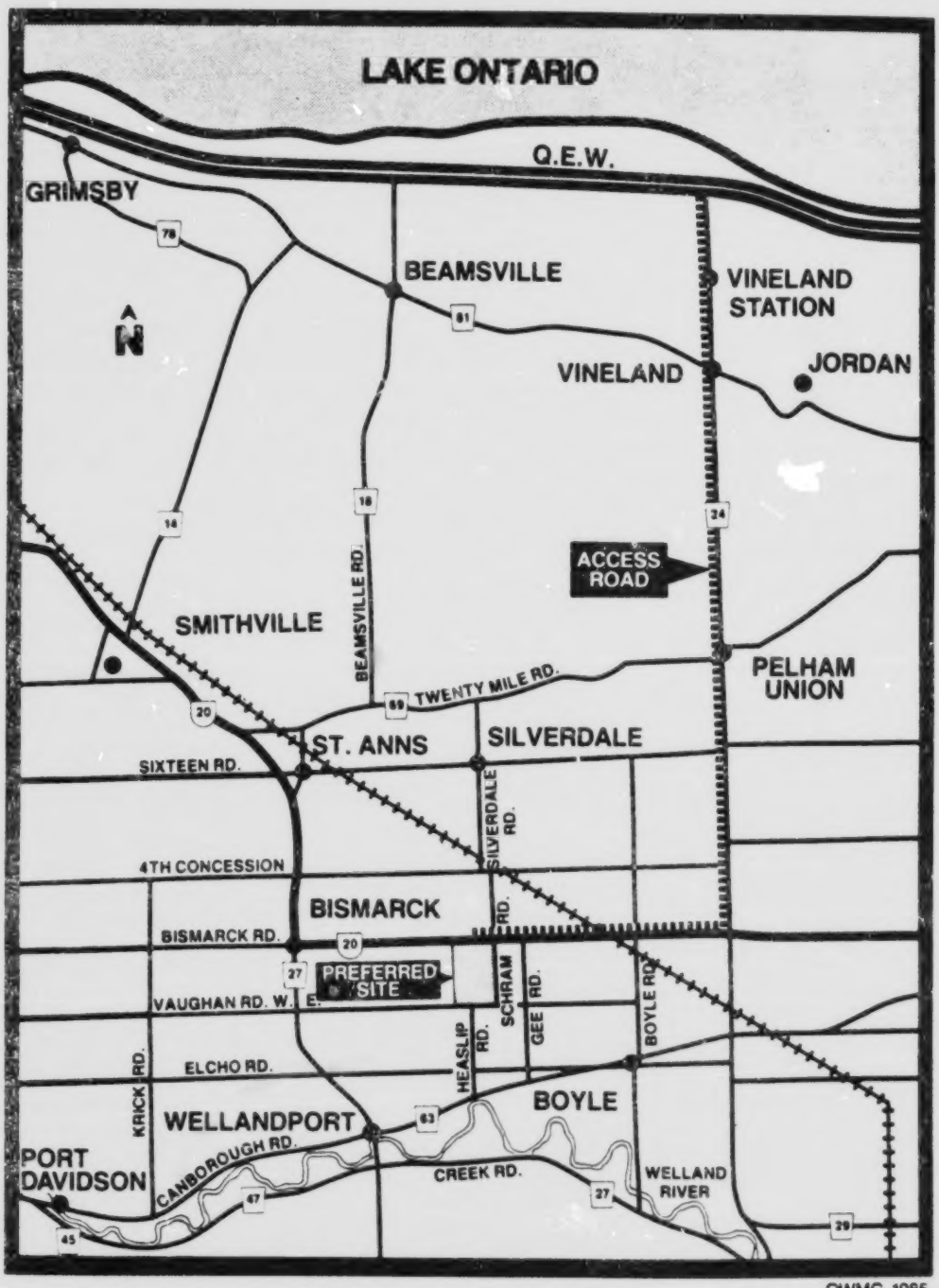
1. Define the existing environmental conditions (baseline) of the Preferred Site,
2. Predict and assess potential risks and impacts that may be associated with the proposed facility design and operations,
3. Identify and develop appropriate mitigative measures to minimize the potential risks and impacts,
4. Interpret residual risks and impacts after mitigation,
5. Identify and develop monitoring programs that will be implemented to assess the
6. Identify and develop contingencies that will be implemented to minimize risks and impacts, and
7. Prepare documentation to meet the requirements of Ontario's Environmental Assessment.

Figure 1-2 illustrates how Phase 4B relates to the other phases of the OWMC Site Assessment and Facilities Development Process.

For the geosciences, Gartner Lee Limited's (GLL) Phase 4B studies have focused on:

1. Establishing baseline conditions for the Preferred Site (GLL 1987b),
2. Providing input to OWMC's engineering consultants for conceptual facilities design (this report and GLL 1987c),

Township of West Lincoln, Regional Municipality of Niagara. Local Detail.



Ontario Waste Management Corporation

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Preferred Site
Figure 1-1

FIGURE 2-3 HYDROGEOLOGIC ASSUMPTIONS FOR LANDFILL CONCEPT EVALUATION

1) Engineering devices (drains, liners, etc.) will fail in time frame measured in tens of years.

2) Leachate of concern will be generated in a time frame measured in terms of hundreds of years.

Therefore:

3) The natural hydrogeologic setting will have to be relied upon to restrict contaminant movement in the long term.

4) Comparison of the landfill design concepts is based on a passive operational mode equivalent to failure of the engineered devices.

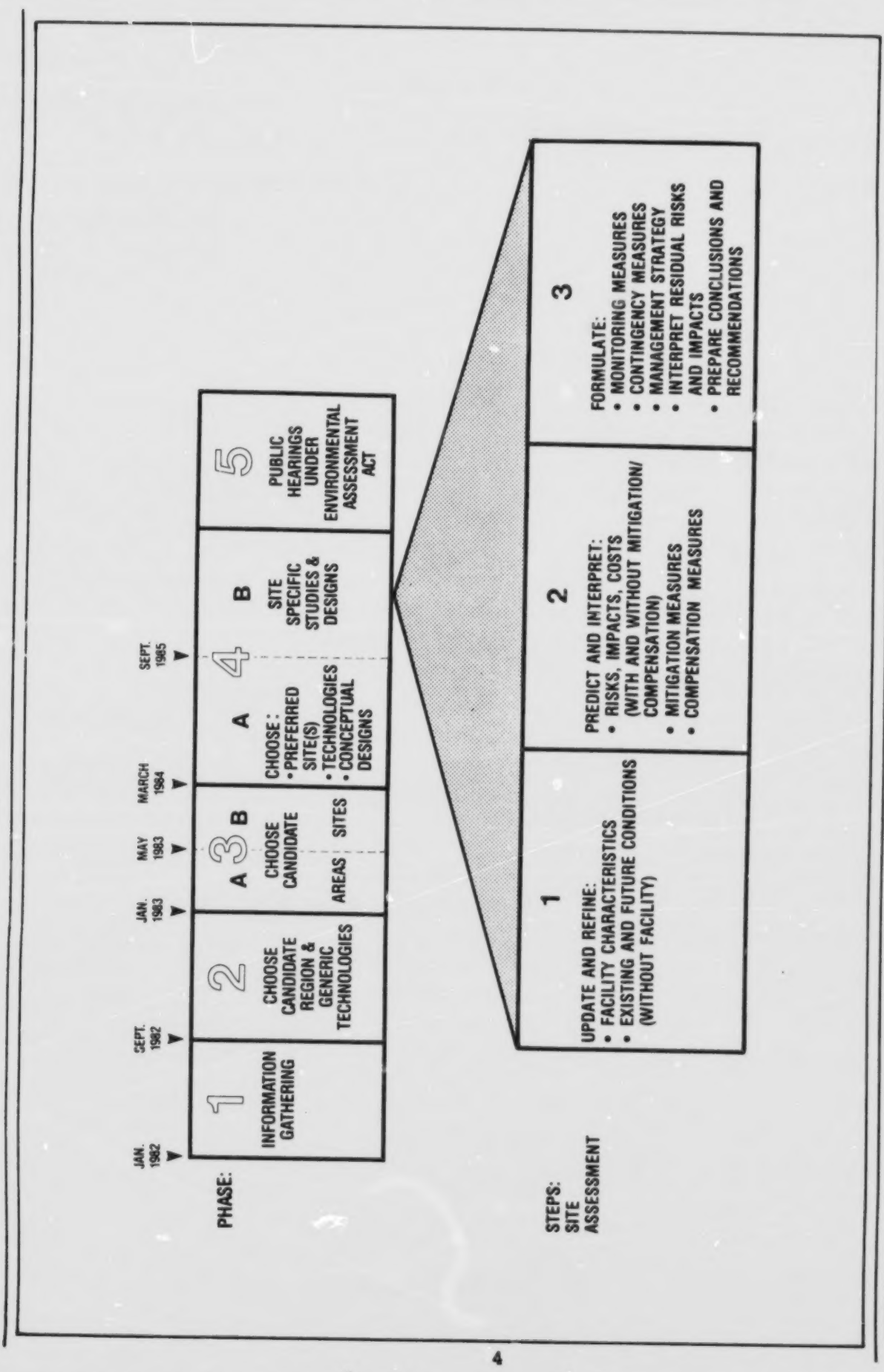


Figure 1.2

FIGURE 2-4 COMPARATIVE EVALUATION OF LANDFILL CONCEPTS - HYDROGEOLOGIC SUB-CRITERIA

CRITERIA	SUB-CRITERIA	ABOVE-GROUND	CONVENTIONAL	SHALLOW ENTOMBED	REMARKS
PERFORMANCE	• DISRUPTION OF NATURAL SURFACE AND GROUND WATER SYSTEMS	MODERATE	MODERATE	LOW*	SHALLOW ENTOMBED CONCEPT MOST CLOSELY RESEMBLES NATURAL SETTING
	• CONTAMINANT TRANSPORT TIME TO UNDERLYING AQUIFER	LONG	LONG	LONG	
	• POTENTIAL FOR OFF-SITE CONTAMINATION RESULTING FROM LATERAL FLOW IN WEATHERED SILT AND CLAY	HIGH	MODERATE	LOW*	FOR SHALLOW ENTOMBED CONCEPT UPWARD DIFFUSION RATES LOW RELATIVE TO DIRECT LEACHATE FLOW FROM OTHER CONCEPTS
	• POTENTIAL FOR DIRECT SURFACE WATER CONTAMINATION	HIGH	MODERATE	LOW*	"MOUND EFFECT" EXPECTED FOR ABOVE-GROUND AND CONVENTIONAL CONCEPTS

* INDICATES BEST RATING FOR SUB-CRITERA

3. Assessing potential ground water impacts from the Central Operation Area (GLL 1987e),
4. Assessing, mitigating and comparing various engineered landfill design concepts as input to OWMC's selection of the shallow entombed landfill (this report),
5. Assessing potential ground water impacts from the shallow entombed landfill, (GLL 1987d), and
6. Developing an overall ground water management plan through monitoring, decommissioning and remedial strategies (GLL 1987f).

Figure 1-3 illustrates how this report fits into GLL's Phase 4B Studies.

1.2 PURPOSE

This report documents the hydrogeologic input provided by Gartner Lee Associates Limited (GLAL) to Ontario Waste Management Corporation's (OWMC) engineering consultants with respect to the conceptual design of the engineered landfill component of OWMC's treatment facility. This report should be considered as a support document to the Process Area Report - Engineered Landfill ("Landfill PAR"; M.M. Dillon, 1986) since the studies presented here were carried out concurrently to provide input to the landfill technology evaluation. Hydrogeologic analysis is considered to be an integral part of the landfill design process.

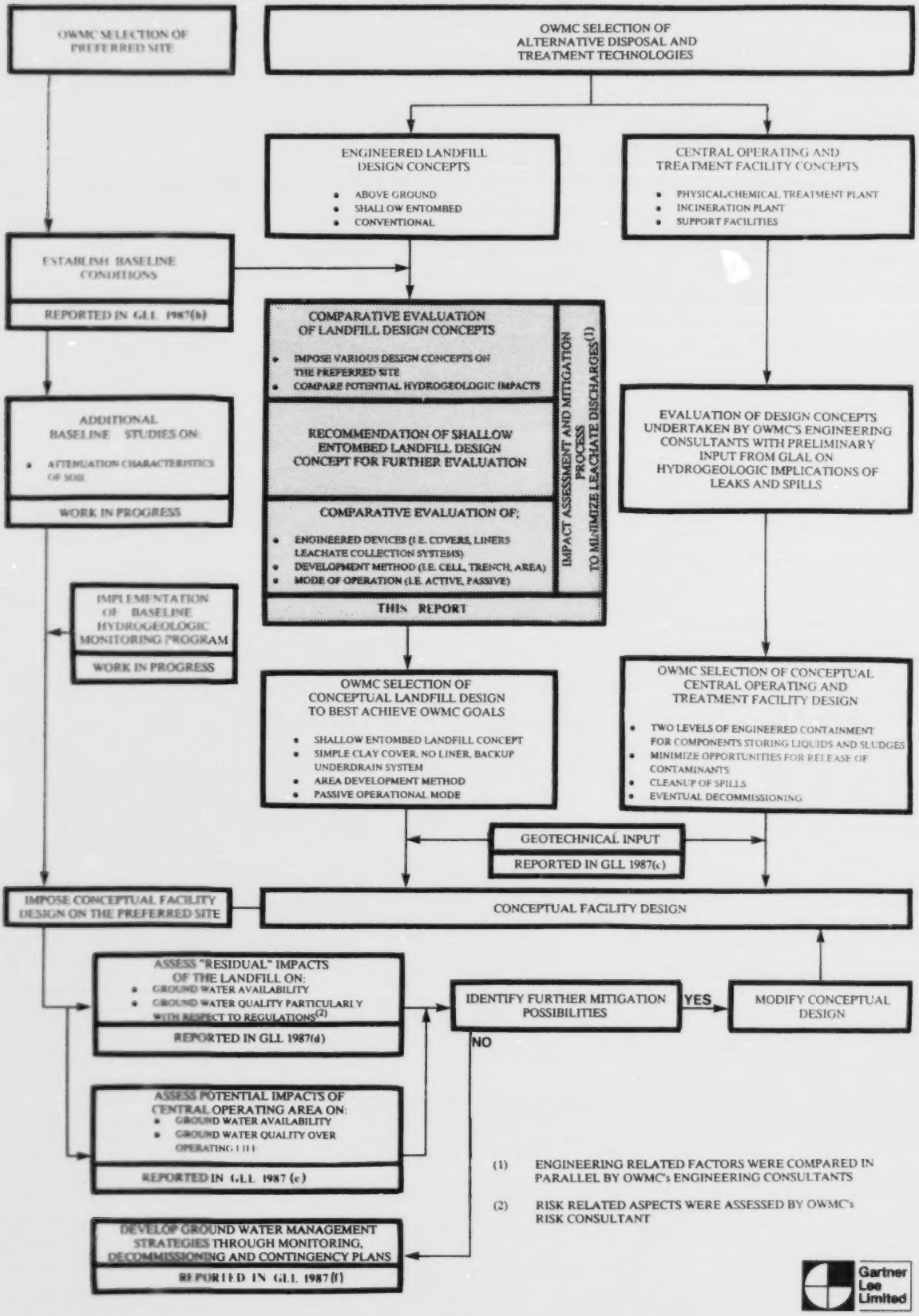
1.3 BACKGROUND

In 1983, GLAL commenced a study of the alternatives for "special" waste disposal in Southern Ontario on behalf of OWMC. The intent of the study was to identify and compare the various waste disposal options, and to recommend which, if any, were practically viable and should be considered for further detailed study.

The report entitled "Evaluation of Alternative Disposal Options" (GLAL, 1986) identified several disposal alternatives including:

(i) deep well disposal,
(ii) land treatment,
(iii) active conventional engineered landfill,
(iv) active above-ground engineered landfill,

FIGURE 1-3
PHASE 4B: IMPACT ASSESSMENT APPROACH: Geoscience


OWMC SELECTION OF PREFERRED SITE
OWMC SELECTION OF ALTERNATIVE DISPOSAL AND TREATMENT TECHNOLOGIES
ENGINEERED LANDFILL DESIGN CONCEPTS
ABOVE GROUND
SHALLOW ENTOMBED
CONVENTIONAL
CENTRAL OPERATING AND TREATMENT FACILITY CONCEPTS
PHYSICAL/CHEMICAL TREATMENT PLANT
INCINERATION PLANT
SUPPORT FACILITIES
ESTABLISH BASELINE CONDITIONS
REPORTED IN GLL 1987(b)
COMPARATIVE EVALUATION OF LANDFILL DESIGN CONCEPTS
IMPOSE VARIOUS DESIGN CONCEPTS ON THE PREFERRED SITE
COMPARE POTENTIAL HYDROGEOLOGIC IMPACTS
RECOMMENDATION OF SHALLOW ENTOMBED LANDFILL DESIGN CONCEPT FOR FURTHER EVALUATION
COMPARATIVE EVALUATION OF:
ENGINEERED DEVICES (I.E. COVERS, LINERS LEACHATE COLLECTION SYSTEMS)
DEVELOPMENT METHOD (I.E. CELL, TRENCH, AREA)
MODE OF OPERATION (I.E. ACTIVE, PASSIVE)
THIS REPORT
IMPACT ASSESSMENT AND MITIGATION PROCESS TO MINIMIZE LEACHATE DISCHARGES(1)
EVALUATION OF DESIGN CONCEPTS UNDERTAKEN BY OWMC'S ENGINEERING CONSULTANTS WITH PRELIMINARY INPUT FROM GLAL ON HYDROGEOLOGIC IMPLICATIONS OF LEAKS AND SPILLS
ADDITIONAL BASELINE STUDIES ON:
ATTENUATION CHARACTERISTICS OF SOIL
WORK IN PROGRESS
IMPLEMENTATION OF BASELINE HYDROGEOLOGIC MONITORING PROGRAM
WORK IN PROGRESS
OWMC SELECTION OF CONCEPTUAL LANDFILL DESIGN TO BEST ACHIEVE OWMC GOALS
SHALLOW ENTOMBED LANDFILL CONCEPT
SIMPLE CLAY COVER, NO LINER, BACKUP UNDERDRAIN SYSTEM
AREA DEVELOPMENT METHOD
PASSIVE OPERATIONAL MODE
OWMC SELECTION OF CONCEPTUAL CENTRAL OPERATING AND TREATMENT FACILITY DESIGN
TWO LEVELS OF ENGINEERED CONTAINMENT FOR COMPONENTS STORING LIQUIDS AND SLUDGES
MINIMIZE OPPORTUNITIES FOR RELEASE OF CONTAMINANTS
CLEANUP OF SPILLS
EVENTUAL DECOMMISSIONING
GEOTECHNICAL INPUT
REPORTED IN GLL 1987(c)
IMPOSE CONCEPTUAL FACILITY DESIGN ON THE PREFERRED SITE
CONCEPTUAL FACILITY DESIGN
ASSESS "RESIDUAL" IMPACTS OF THE LANDFILL ON:
GROUND WATER AVAILABILITY
GROUND WATER QUALITY PARTICULARLY WITH RESPECT TO REGULATIONS(2)
REPORTED IN GLL 1987(d)
IDENTIFY FURTHER MITIGATION POSSIBILITIES
YES
MODIFY CONCEPTUAL DESIGN
NO
ASSESS POTENTIAL IMPACTS OF CENTRAL OPERATING AREA ON:
GROUND WATER AVAILABILITY
GROUND WATER QUALITY OVER OPERATING LIFE
REPORTED IN GLL 1987 (e)
DEVELOP GROUND WATER MANAGEMENT STRATEGIES THROUGH MONITORING, DECOMMISSIONING AND CONTINGENCY PLANS
REPORTED IN GLL 1987 (f)
(1) ENGINEERING RELATED FACTORS WERE COMPARED IN PARALLEL BY OWMC's ENGINEERING CONSULTANTS
(2) RISK RELATED ASPECTS WERE ASSESSED BY OWMC's RISK CONSULTANT
Gartner Lee Limited

(v) passive deep entombed engineered landfill,

(vi) passive shallow entombed engineered landfill,

(vii) disposal in existing mines in Precambrian rocks,

(viii) disposal in existing mines in Paleozoic rocks.

The viability of each of these alternatives is discussed in the report. GLAL concluded that three of the engineered landfill alternatives, namely the above-ground, conventional, and shallow entombed, were viable and recommended that further evaluation of these concepts be undertaken.

One of the premises of the study was that all landfill designs were assumed to be located in thick, fine-grained soils of low permeability. Earlier discussions had concluded that low permeability soils were preferable because they tend to naturally retard contaminant movement. The preference for thick, low permeability soils was subsequently used as a fundamental factor in the site selection process (GLAL 1983; 1987b).

In 1984, GLAL conducted more detailed analyses of the above-ground, conventional, and shallow entombed engineered landfill concepts. Using computer modelling techniques, each concept was assessed in a hypothetical geologic environment consisting of fine-grained, low permeability soils about 25 metres thick overlying a bedrock aquifer. Although at that time the work was generic in scope, Site LF-9C which OWMC has selected as its Preferred Site has hydrogeologic conditions very similar to those assumed in the generic modelling work.

The results of the generic modelling work are documented in a Working Paper (GLAL 1987a). Although that study provided guidance with respect to the choice of landfill design concept, GLAL recommended that OWMC not make a final decision until such time as the preferred site was chosen and input was obtained from the engineering consultants.

In recognition of the fact that the site setting would be an integral component in the design of the engineered landfill, a Landfill Working Group was formed in 1985. This

group consisted of representatives from Gartner Lee Associates Limited, Monenco Limited, and M.M. Dillon Limited. GLAL's role as part of this group was to provide the engineering consultants with geologic, hydrogeologic, and geotechnical input to the design of the engineered landfill. The work undertaken by the Landfill Working Group culminated with the publication of the Landfill PAR (M.M. Dillon, 1986).

1.4 SCOPE AND METHODOLOGY

The Landfill PAR (M.M. Dillon, 1986) incorporates the GLAL input to the engineered landfill design. This report provides a more detailed account of the hydrogeologic input supplied by GLAL to the design of the engineered landfill as described in the Landfill PAR.

Readers who are unfamiliar with the geologic, hydrogeologic, and geotechnical conditions at the Preferred Site are referred to the report entitled "Site Assessment Phase 4B: Geology, Hydrogeology and Geotechnics, Baseline Conditions" which describes the natural site setting (GLAL, 1987b). A knowledge of the baseline conditions for the site are assumed in this report .

Each of the chapters of the report present the hydrogeologic analysis of the engineered landfill components, namely:

- landfill concept (Chapter 2.0),
- landfill engineered devices (Chapter 3.0),
- landfill operational mode (Chapter 4.0), and
- landfill development method (Chapter 5.0).

The general methodology for the analysis of these components was:

(1) identify alternatives,
(2) undertake a comparative evaluation, and
(3) select a preferred alternative.

The methodologies are discussed in detail at the beginning of each of the following chapters.

As noted, this report presents a comparative evaluation of only the hydrogeologic factors. Engineering-related factors were also evaluated which, together with the hydrogeologic factors, formed a complete comparative evaluation. This is documented in the Landfill PAR (M.M. Dillon, 1986).

The last chapter of this report (Chapter 6.0) describes additional hydrogeologic inputs provided by GLAL to the engineered landfill design. These include:

- hydrogeologic implications of excess clay stockpiles (Section 6.1),
- hydrogeologic implications of surface water drainage design on landfill cover (Section 6.2),
- hydrogeologic implications of size, design, and locations of the proposed landfill storm detention pond (Section 6.3),
- estimates of leachate quantities in active operational mode (Section 6.4), and
- hydrogeologic input to the design of the underdrain system (Section 6.5).

All external (i.e., other OWMC consultants) inputs to this study are identified where they occur in the text. In this report, all inputs are obtained from the engineering consultant M.M. Dillon Ltd.

The two waste input scenarios (150,000 vs. 300,000 tonnes per annum) do not affect the studies presented in this document, and are therefore not considered separately here.

OWMC has established a list of factors that have been consistently applied in the evaluation of technologies. Those that apply to the analyses presented in this report are (OWMC, 1987):

- Ground Water, and
- Surface Water.

Within each of these factors, indicators are developed which allow for points of comparison specific to the characteristics of individual technologies. From the perspective of the hydrogeologic performance assessments contained in this report, the related indicators are generally:

Ground Water

- potential impacts on ground water flow (availability), short-term and long-term,
- potential impacts on ground water quality, short-term and long term,

Surface Water

- potential for surface water contamination as a result of ground water discharges, short-term and long term.

Gartner Lee's studies documented in this report have been formally input to the Environmental Assessment documentation via the Landfill PAR (M.M. Dillon, 1986).

2.0 LANDFILL CONCEPT

2.1 INTRODUCTION

This section provides details regarding the hydrogeologic input to the selection of a preferred engineered landfill design concept. The three concepts under consideration in this report were those identified as being feasible in the report "Evaluation of Alternative Disposal Options" (GLAL 1986a), namely:

- above-ground landfill concept,
- shallow entombed landfill concept,
- conventional landfill concept.

Figure 2-1 shows each of the three landfill concepts schematically.

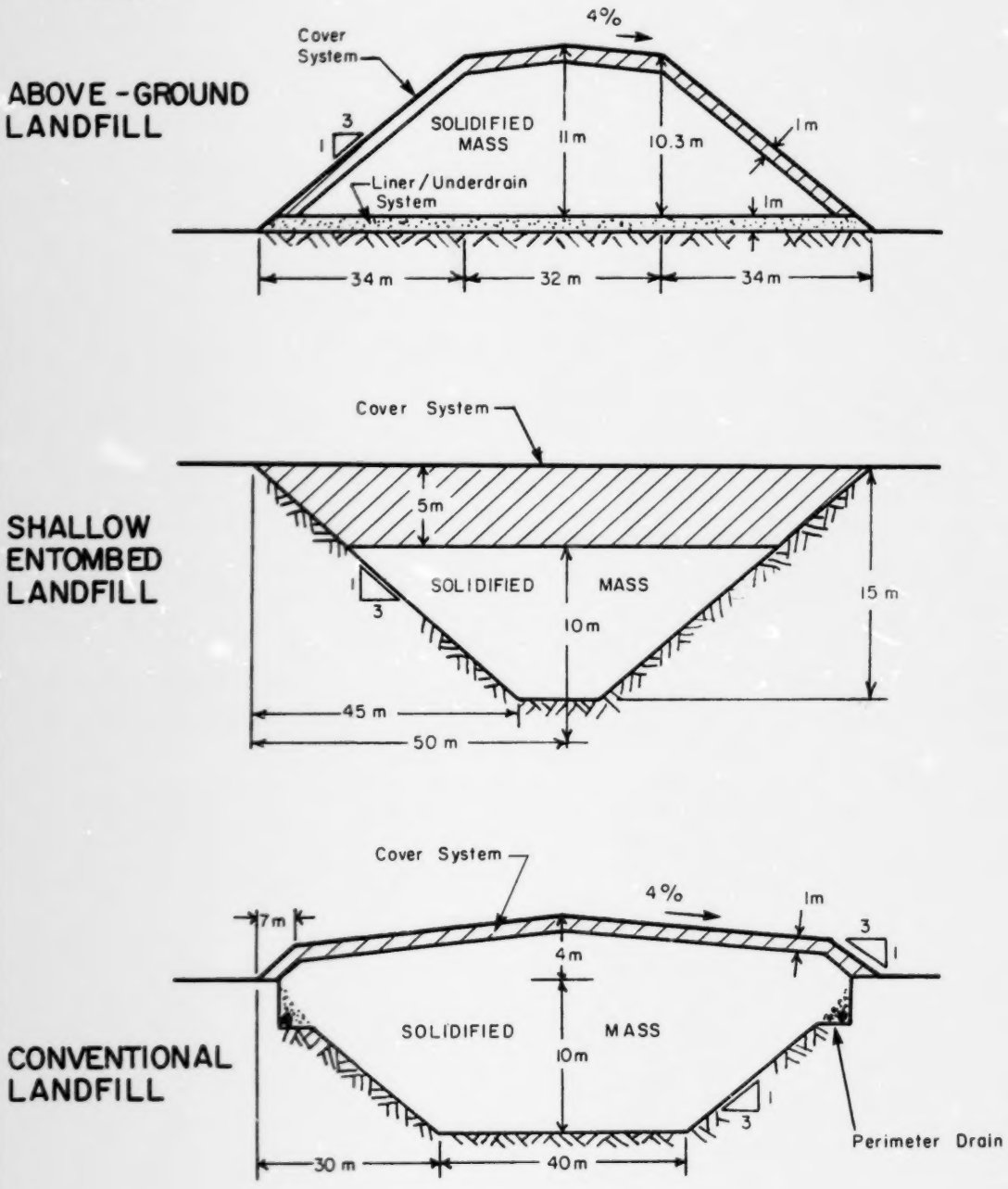
The above-ground concept places the solidified mass entirely above the ground surface and isolates it from the surficial weathered silt and clay soils through the use of a liner and drainage system. A final cover is provided over the waste to act as an infiltration barrier. At the Preferred Site, the above-ground landfill could be constructed to a height of about 12 metres above ground surface based on preliminary geotechnical data (GLAL, 1985).

The shallow entombed concept places all of the solidified mass below the base of the weathered silt and clay, which is assumed to be about 5 metres thick based on data from the geoscience investigations (GLAL 1987b). The cover system is placed on top of the solidified mass and is completed at about original ground surface level. Liners and drainage systems are optional features of this concept. The maximum allowable depth of excavation at the Preferred Site is about 15 metres for the shallow entombed concept (GLAL, 1985b).

The conventional concept places the solidified mass both above and below ground surface. An infiltration barrier is provided by the cover system. Liner and underdrainage systems are optional for this concept, but as a minimum a perimeter drain would be considered necessary to control ground water discharges to surface

FIGURE 2-1

LANDFILL CONCEPTS IN SITE ADAPTED FORM



(ADAPTED FROM M.M. DILLON, 1986)

Gartner Lee Limited

and to the weathered silt and clay. Based on preliminary geotechnical analysis, a total depth of 10 metres and a total height of 4 metres are possible at the Preferred Site (GLAL, 1985b).

2.2 METHODOLOGY

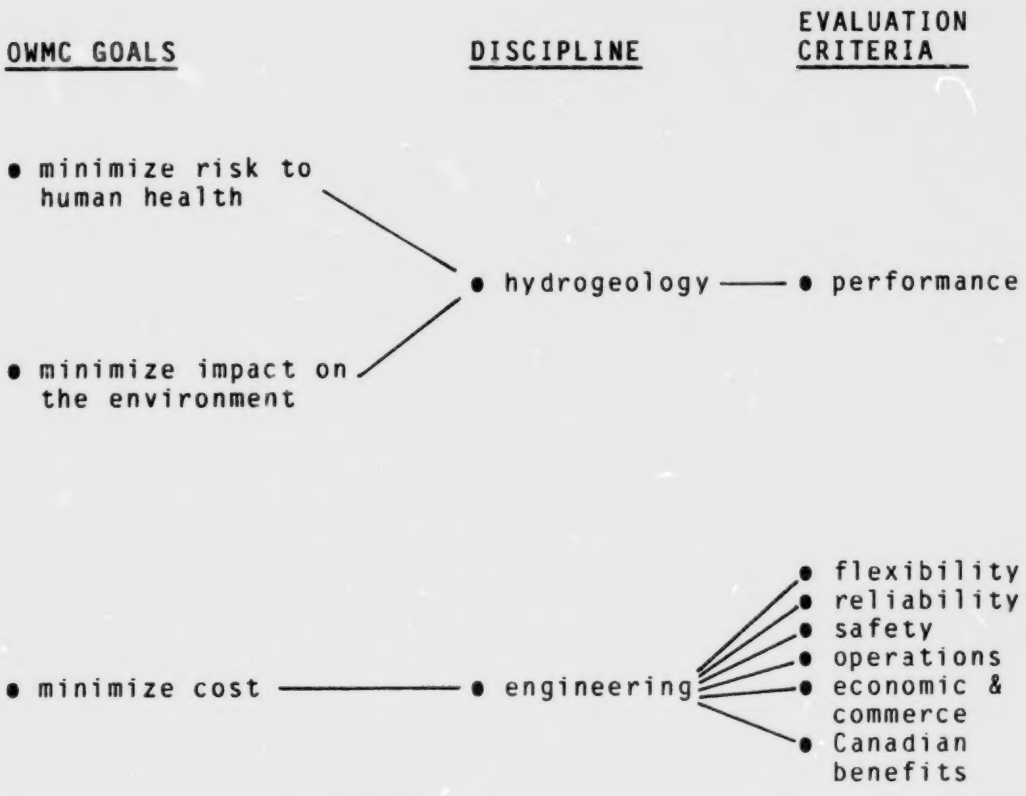
The assessment and comparison of the three engineered landfill design concepts was based on the technology evaluation procedure developed for the selection of other facility components (M.M. Dillon 1986). It involves a detailed comparison of each alternative with respect to the following criteria:

- performance,
- flexibility,
- reliability,
- safety,
- operational considerations,
- economic and commercial considerations, and
- Canadian benefit.

A portion of the first criterion, performance, was considered to be hydrogeologic-related and was assessed by GLAL. The results are presented in this report. The remainder were considered to be engineered-related and were therefore primarily addressed by M.M. Dillon Limited with inputs from Monenco and GLAL. The overall results of the comparative evaluation are documented in the Landfill PAR (M.M. Dillon 1986). Input was provided by GLAL to portions of the assessment of the operational considerations criteria, in particular off-site effects due to clay import/export and ease of monitoring. However, GLAL's input is presented in context in the Landfill PAR and will not be repeated in this Report.

Figure 2-2 shows how the criteria employed in the evaluation of alternative landfill design concepts relates directly to OWMC's established goals of minimizing risk to human health, minimizing impact on the environment, and minimizing cost.

FIGURE 2-2 RELATIONSHIP OF EVALUATION METHODOLOGY TO OWMC GOALS



Within each criterion, sub-criteria were established which allowed for specific points of comparison. In terms of hydrogeologic performance, the sub-criteria were established to reflect the factors which relate to potential impacts of the facility, that is, impacts on ground water flow, impacts on ground water quality and impacts on, surface water which could receive leachate. The following were the resulting hydrogeologic performance sub-criteria:

- disruption of natural surface and ground water systems,
- contaminant transport time to the underlying bedrock aquifer,
- potential for off-site contamination resulting from lateral weathered zone flow, and
- potential for direct surface water contamination.

Several basic assumptions were required in order to evaluate the landfill concepts. These are summarized in Figure 2-3. The significance of these will be discussed in the following section which presents the results of the evaluation.

2.3 COMPARISON OF CONCEPTS

The hydrogeologic performance of each of the three alternative landfill concepts was compared on established sub-criteria. The results are summarized in Figure 2-4. The concept which provides optimal benefits with respect to each sub-criterion is indicated by an asterisk.

It is important to note that this comparison considers long-term hydrogeologic performance only. That is, any engineered devices (e.g. underdrains, liners, etc.) are assumed to have failed prior to the decay of the source of contaminants within the landfill. These assumptions were outlined in Figure 2-3. The following provides the rationale for the ratings shown in Figure 2-4.

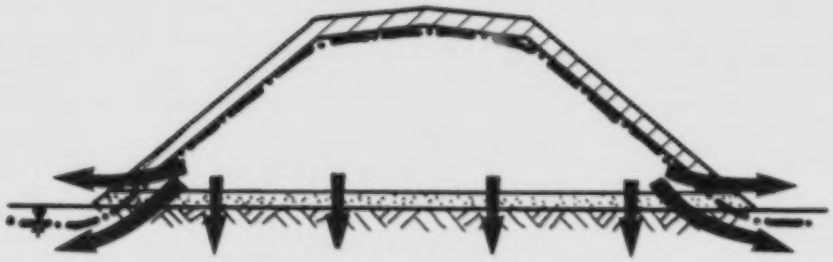
2.3.1 Disruption of Natural Surface and Ground Water Systems

This sub-criteria considers the cumulative impact that a particular landfill concept may have on the natural flow of surface and ground water at the site. Figure 2-5 schematically illustrates the long-term changes that were predicated based on the

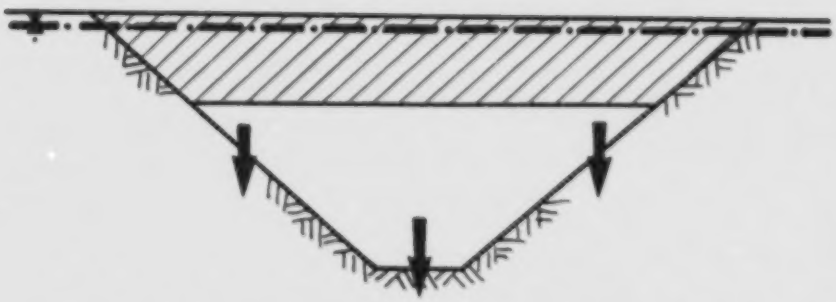
FIGURE 2-5

POTENTIAL LONG TERM PERFORMANCE

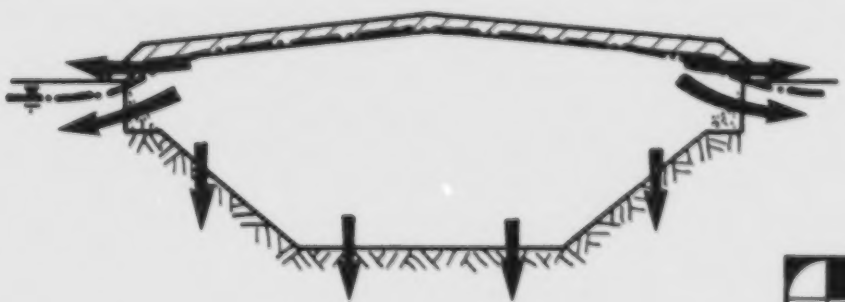
ABOVE-GROUND LANDFILL



SHALLOW ENTOMBED LANDFILL



CONVENTIONAL LANDFILL



Predicted Water Table

Arrows Show Ground Water Flow

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results of ground water flow modelling (GLAL 1987a). In each case, the local water table is expected to occur near the ground surface, as it does presently at the site (GLAL 1987b). This is a result of the very low permeability of the silt and clay soils which restrict the downward flow of ground water. The ground water "mound" which would form as a consequence in the above-ground and conventional landfill concepts manifests itself as an overall increase in hydraulic head. This would result in surface water discharges around the landfill perimeter, increased lateral ground water flow rates in the weathered silt and clay around the landfill, and increased downward ground water flow rates in the silt and clay soils beneath the landfill relative to the natural rates of flow at the site. Because of their low permeability, however, downward flow rates would still be considered extremely slow.

By contrast, the shallow entombed concept has no above-grade component and hence no ground water mound can form. The only significant difference between the completed shallow entombed landfill and the natural site conditions would be the contrast in physical properties (e.g. hydraulic conductivity) between the solidified mass and the native silt and clay which it replaces. Consequently, minimal disruption to the natural surface water and ground water flow systems were predicted (GLAL 1987a).

2.3.2 Contaminant Transport Time to Underlying Aquifer

Simple, one-dimensional advection-dispersion contaminant transport models were used to predict, for comparative purposes, the time required for contaminants to reach the underlying aquifer at the site (GLAL 1987a; 1985). Although slight differences were noted between the various landfill concepts, in general, the time required for contaminant breakthrough at the aquifer is considered to be long for all three (for example, greater than 700 years for break through to 10% of source concentration). For this reason, the concepts were ranked equally for this sub-criterion.

2.3.3 Potential for Off-Site Contamination Resulting From Lateral Weathered Zone Flow

Presently, natural ground water flow in the weathered silt and clay is thought to be controlled by the surficial ridge and swale topography evident at the site. Because these features have low overall topographic relief and are relatively closely spaced, the

gradients and flows are considered to be localized (GLAL 1987b). However, the introduction of a ground water mound in either the above-ground or conventional landfill (more so for the above-ground because it is farther above grade) concepts may result in more extensive lateral flow in the weathered silt and clay. In either concept, solidified mass is placed on or within the weathered zone. Assuming long-term failure of drains and liners, contaminants would be in direct contact with the hydrogeologically active portion of the weathered silt and clay and thus could potentially be transported off-site in the weathered silt and clay.

The shallow entombed concept, on the other hand, retains the ridge and swale topography (recreated at surface) and does not allow a ground water mound to form. Therefore, gradients and flows in the weathered silt and clay will remain localized. Furthermore, the solidified mass is placed below the hydrogeologically active portion of the weathered silt and clay which isolates it from shallow, surficial ground water flow. The only means by which contaminants could reach the weathered zone would be by upward diffusion through the cover, which is a very slow process capable of transporting only very small quantities of contaminants. For these reasons, the potential for off-site contaminant transport in the weathered silt and clay has been rated as low for the shallow entombed concept in Figure 2-4.

2.3.4 Potential For Direct Surface Water Contamination

As discussed previously and illustrated in Figure 2-5, ground water seepages around the landfill perimeter are predicted for the above-ground and conventional landfill concepts (again, more so for the above-ground because of the greater potential mounding) in the long-term as a result of ground water mounding within the landfill. These seepages have the potential to contaminate the surface drainage system around the landfill. This suggest that perpetual surface water control, monitoring, and treatment may be required for these concepts.

The shallow entombed landfill concept is rated as having a low potential for direct surface water contamination. The only natural mechanism by which contaminants could reach the surface water system would be by upward diffusion, which is a slow process capable of transporting only very small quantities of contaminants relative to

the total amount of dilution available in the surface water system. It is probable, then, that long-term surface water control would not be required for the shallow entombed landfill concept.

2.4 RECOMMENDATION

Examination of Figure 2-4 shows that the shallow entombed landfill concepts achieved the best rating in four of the five performance sub-criteria and was ranked equally with the above-ground and conventional concepts in the other. For this reason, shallow entombed was put forward as the preferred landfill concept on the basis of hydrogeologic criteria (performance), which corresponds directly to the OWMC goals of minimizing risk to human health and minimizing impact to the environment (Figure 2-2).

Overall, shallow entombed was also considered to be the preferred landfill concept based on the complete evaluation including the engineering related criteria, and was recommended as the proposed landfill concept for preliminary engineering design (M.M. Dillon 1986).

3.0 LANDFILL ENGINEERED DEVICES

3.1 INTRODUCTION

Engineered devices are design features of a landfill whose purpose is to allow a degree of control over contaminant migration. The following introduces the three basic engineered devices under consideration here and a brief statement of their function:

- cover system - low permeability layer(s) placed over the completed landfill to reduce infiltration from the surface and hence minimize the production of leachate;

- liner system - low permeability layer(s) placed beneath the solidified mass to minimize seepage of leachate into underlying soils;

- drainage system - high permeability conduit(s) and/or granular layers placed beneath or around the solidified mass to allow for the removal of leachate.

Within the basic framework of each of these devices, various alternative designs can be considered. The following were included in this evaluation:

- cover systems
  - (a) simple - recompacted native silt and clay
  - (b) composite - including a synthetic barrier(s)

- liner systems
  - (a) none
  - (b) simple - recompacted native silt and clay
  - (c) composite - including a synthetic barrier(s)

- drainage systems
  - (a) none
  - (b) perimeter drains
  - (c) underdrains

Detailed descriptions of these various devices are contained in the Landfill PAR (M. M. Dillon 1986). Two operational modes were included in the evaluation:

- active mode: drainage system operational
- passive mode: drainage system not operated (contingency/monitoring use only). failed, or not in place.

3.2 METHODOLOGY

A detailed comparative evaluation of the large number of possible combinations of engineered devices and operational modes was not practical. Therefore, preliminary hydrogeologic and engineering assessments of the various devices were performed in order to develop several representative, balanced systems of devices that could be evaluated in detail. The preliminary hydrogeologic assessment is presented in Section 3.3, while the preliminary engineering assessment is provided in the Landfill PAR (M. M. Dillon 1986).

The preliminary hydrogeologic assessment was based partially on quantitative support from ground water flow modelling. In addition to the Phase 4A modelling results used in the selection of the shallow entombed landfill concept (GLL 1987a), further modelling was performed using preliminary Phase 4B data. The later modelling is presented in the following sections, although the supporting documentation and discussion of boundary conditions for the "SSWT" ground water flow model is provided in the earlier report (GLL 1987a). It is important to note that since this evaluation is comparative in nature, the additional level of detail that resulted from the completion of the Phase 4B work (GLL 1987b) does not affect the results and conclusions presented here.

Four systems of engineered devices were developed based on the preliminary assessment. The comparative evaluation of these systems is presented in Section 3.4. The same methodology was used as for the selection of the landfill concept (see Section

2.2). Here, the same criteria were used in the comparison; however, the sub-criteria were altered to be more specific to the evaluation of systems of engineered devices.

This report considers only the hydrogeologic performance criteria. The remainder of the criteria are engineering-related and are evaluated in the Landfill PAR (M. M. Dillon 1986). Because the engineered devices were shown in the preliminary engineering assessment to have varying lifespans and only some were considered repairable, two performance criteria were used:

- short-term performance - all devices operational.
- long-term performance - all non-repairable devices have failed.

In the selection of the shallow entombed landfill concept, minimal impact on ground water flow was ensured. Therefore, the sub-criteria for the comparative evaluation of the four systems of devices concentrated on ground water quality. The following sub-criteria were employed:

- rate of contaminant transport to aquifer,
- rate of contaminant transport to surface, and
- rate of contaminant transport in weathered silt and clay.

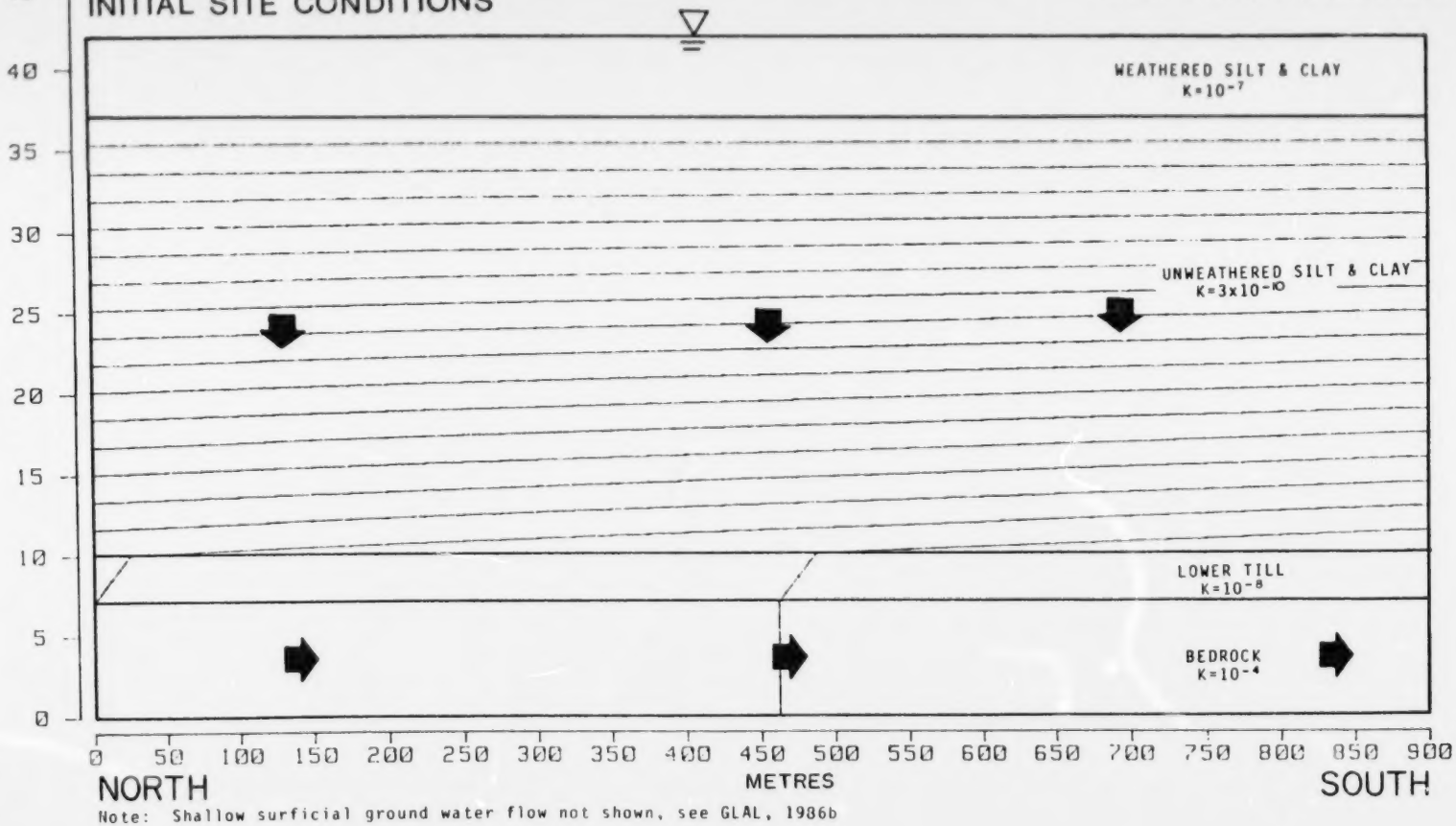
3.3 PRELIMINARY ASSESSMENT AND DEVELOPMENT OF SYSTEMS OF ENGINEERING DEVICES

An idealized north to south cross section of the Preferred Site is shown for reference in Figure 3-1. (Note: Figure 3-1 is an idealized cross section for illustration of ground water flows. The Preferred Site is actually about 1400 m north-south.) The two major hydrostratigraphic groups are the aquitard (composed of the weathered silt and clay, unweathered silt and clay, and lower till) and the bedrock aquifer. The values of hydraulic conductivity used in the assessment are indicated for each unit.

The hydraulic head distribution calculated by ground water flow modelling is illustrated by the equipotential contours (lines of equal hydraulic head). At true scale, ground

FIGURE 3-1
INITIAL SITE CONDITIONS

Vertical exaggeration approx. 11x
equipotential contour interval = 0.5 m
K is hydraulic conductivity in m/s
Arrows illustrate ground water flow directions



Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

water flow is perpendicular to the equipotential contours; however, the vertical exaggeration must be accounted for in Figure 3-1. The arrows show examples of approximate ground water flow directions interpreted from the results.

Figure 3-1 shows that ground water flow is vertically downward through the aquitard and laterally to the south in the bedrock aquifer. A shallow flow system occurs at the surface which is not illustrated here due to the disparity in scale. In essence, the bulk of infiltration flows laterally in the shallow subsurface of the weathered silt and clay and discharges into the surface water system via the swales that occur on the surface. Specific discharge (ground water flux) through the unweathered silt and clay is very low (less than 3 mm/a) because of its low permeability. Specific discharge through the bedrock is also relatively low for an aquifer (about 3 m/a) as a result of the low lateral gradient. A more detailed discussion of the natural site hydrogeology may be found in the Phase 4B baseline conditions report (GLL 1987b).

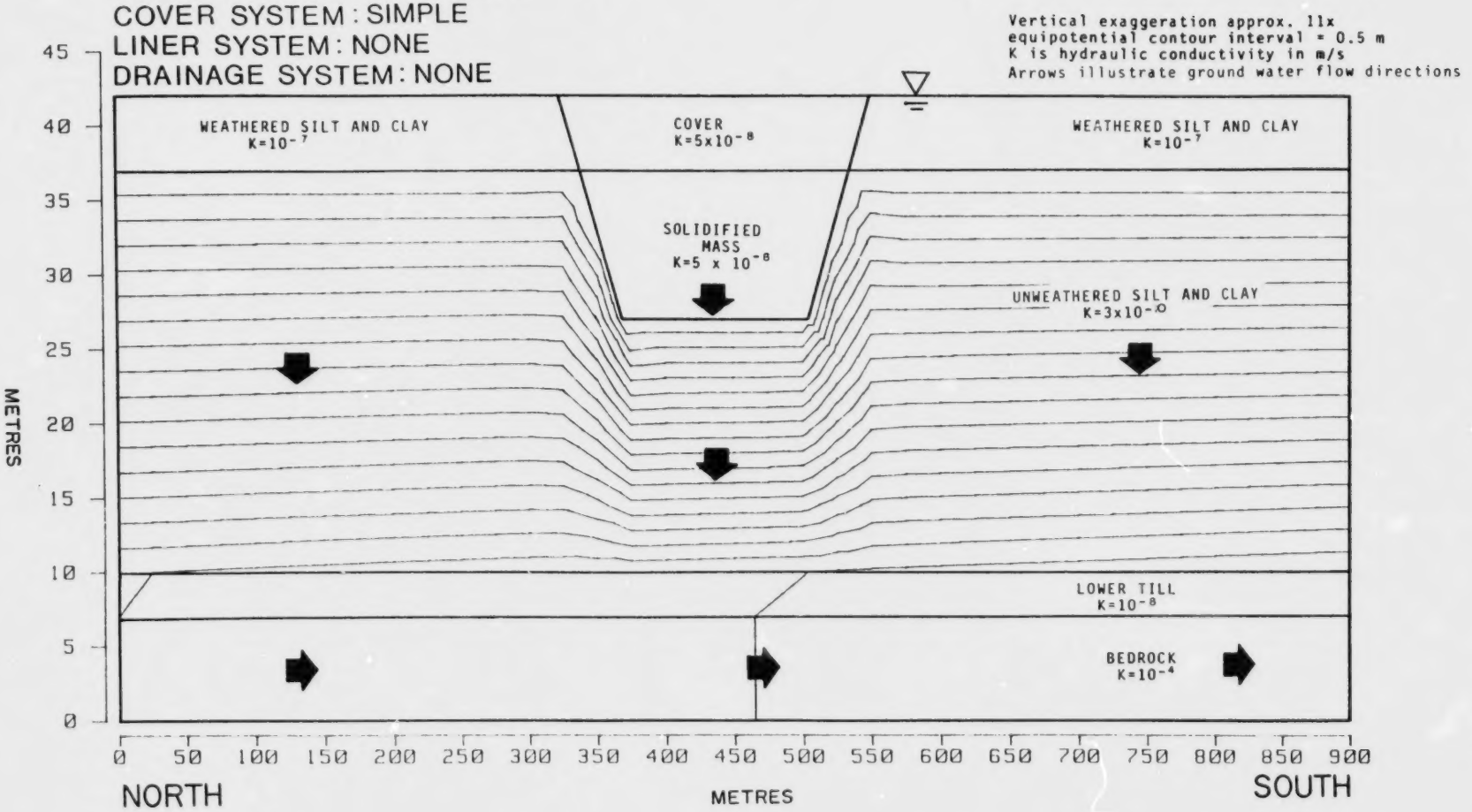
The following provides a preliminary assessment of the hydrogeologic performance of the various alternative devices relative to the natural site hydrogeology described above.

3.3.1 Base Case - No Engineered Devices

Figure 3-2 demonstrates the effect of imposing the most basic form of a shallow entombed landfill cell on the natural hydrogeologic setting. (Note: A single "cell" is used for evaluation purposes. Actual cell sizes may vary.) This system has no liner, no drainage system and a simple cover consisting of recompacted native silt and clay. This system can only be operated in a passive mode.

The equipotential contours indicate that the impact on ground water flow is limited to directly beneath the landfill. The closer spacing of the equipotentials beneath the landfill are indicative of a larger hydraulic gradient, resulting in a rate of ground water flow into the aquifer beneath the landfill that is about 60% greater than in the surrounding areas.

FIGURE 3-2 : BASE CASE EVALUATION
OPERATING MODE: PASSIVE
COVER SYSTEM : SIMPLE
LINER SYSTEM : NONE
DRAINAGE SYSTEM : NONE



Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

3.3.2 Cover Systems

(a) Simple Cover Systems

Simple cover systems are considered to consist only of recompacted native material which is contoured at surface to provide surface water control. Within this definition, the only significant design variable would be the degree of compaction, and hydraulic conductivity, attained. The Base Case, Figure 3-2 assumes a hydraulic conductivity value intermediate between the weathered and unweathered silt and clay. Figures 3-3 and 3-4 examine the two extremes that might be expected. If the cover were to become as weathered as the in-situ surficial materials in the long-term, then Figure 3-3 demonstrates that there would be very little change in performance expected relative to the Base Case. This is due to the fact that the unweathered silt and clay underlying the landfill has a significantly lower hydraulic conductivity than the cover and therefore is the dominant factor in limiting downward flow.

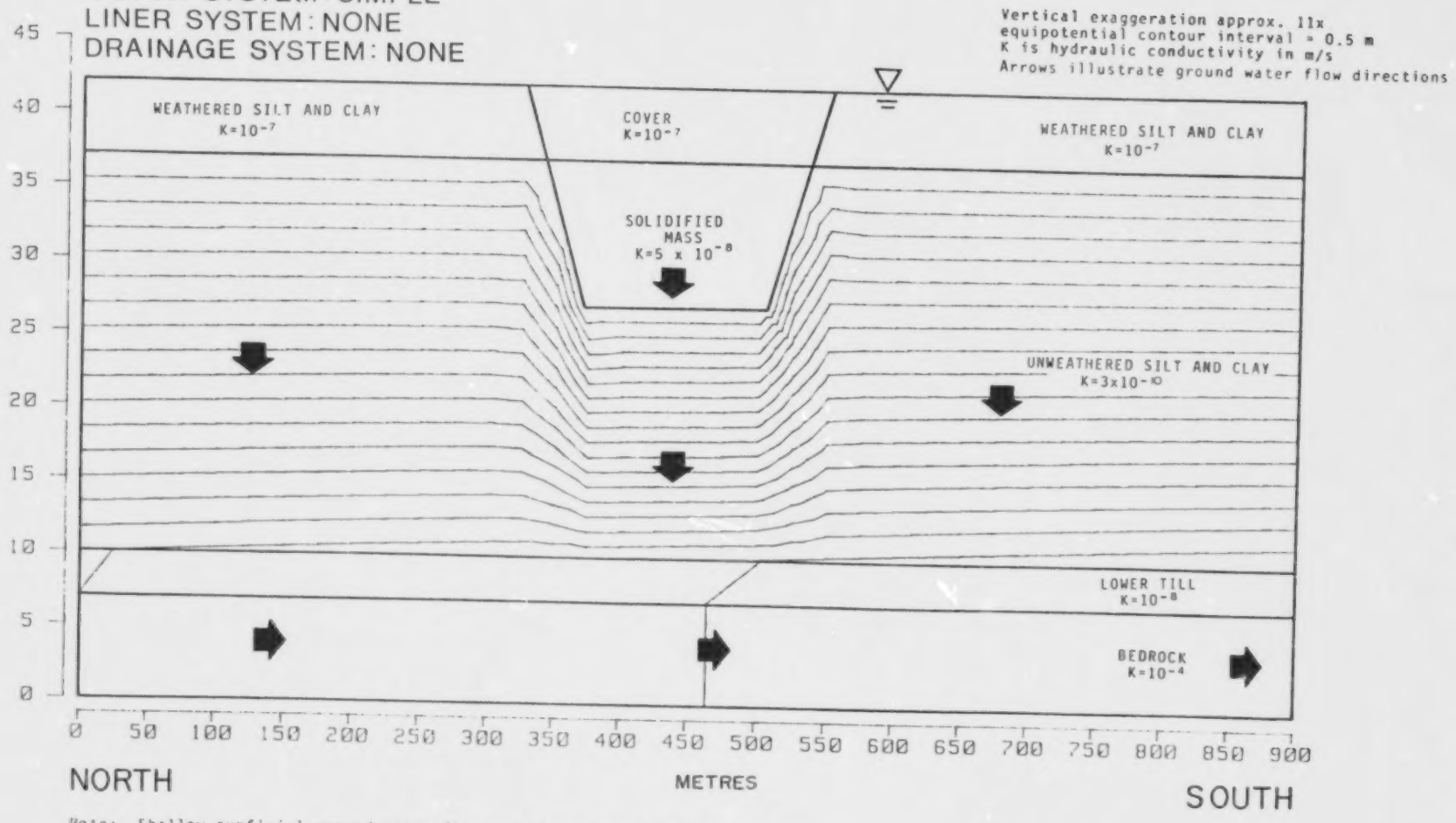
Figure 3-4 suggests that if the cover system can be constructed and maintained with a hydraulic conductivity equal to or lower than that of the unweathered silt and clay, then some effect will occur. In this case, infiltration through the cover is decreased, however, discharge from the base of the landfill is not greatly different from the Base Case. This is due to the fact that additional inflow is induced along the sides of the landfill.

(b) Composite Cover Systems

The purpose of a composite cover system is to produce low infiltration rates into the solidified mass. This can be achieved through the use of barrier layers in the cover. Barrier layers may consist of synthetic materials such as plastic membranes or admixtures of natural geologic materials. A more thorough discussion of these barriers is contained in Section 3.3.3 which follows.

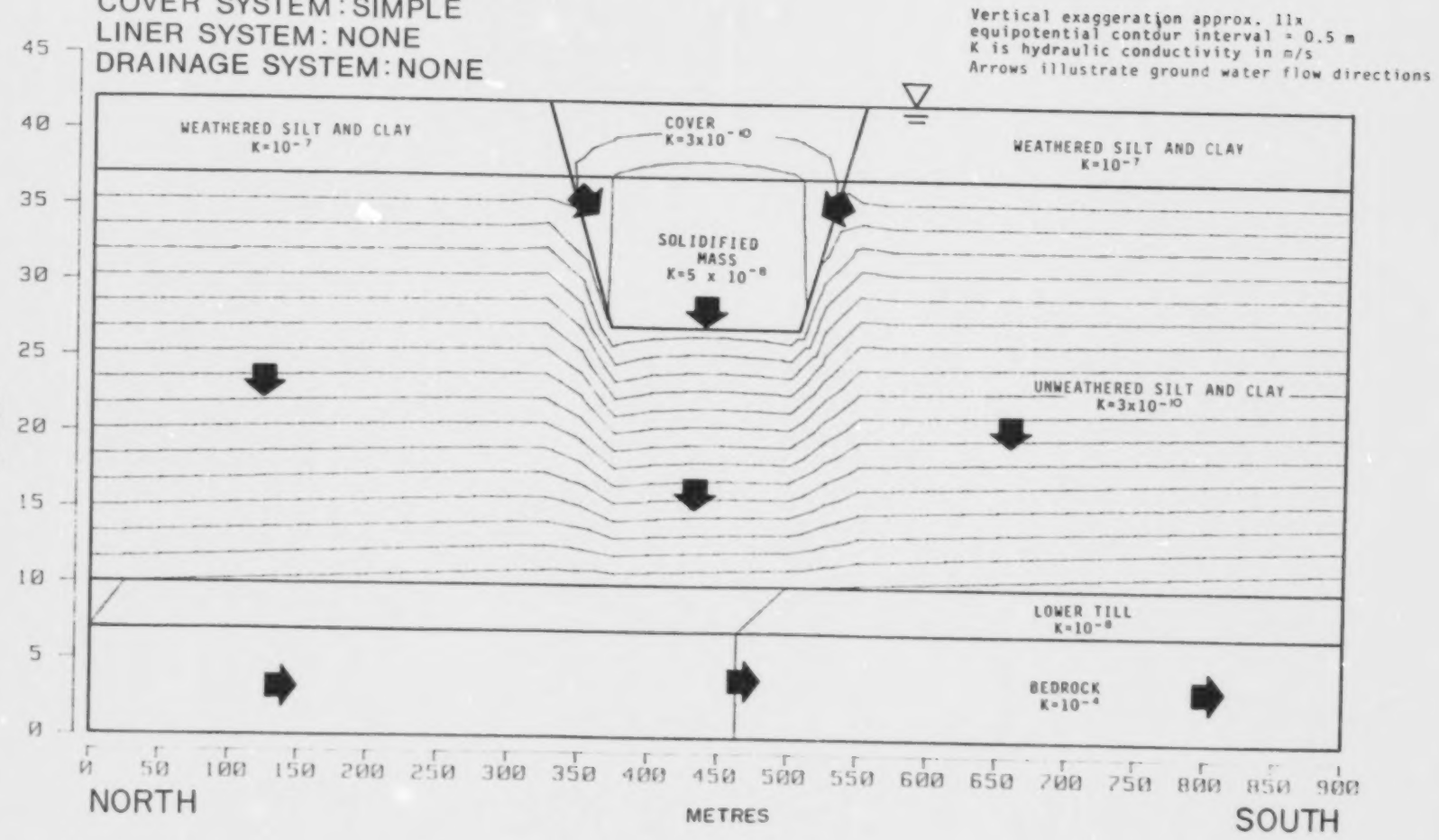
Figures 3-5 and 3-6 demonstrate the flow systems that result from the inclusion of barriers with hydraulic conductivities of 1×10^{-11} m/s and 1×10^{-14} m/s respectively at the base of the cover system. The modelling results indicate that infiltration through the cover is indeed reduced to low levels. However, the decreased infiltration is somewhat offset by increased inflow along the side of the landfill, particularly around the perimeter of the barrier. As a result, the rate of leachate flow from the base of the

FIGURE 3-3 : SIMPLE HIGHER PERMEABILITY COVER EVALUATION
OPERATING MODE: PASSIVE
COVER SYSTEM : SIMPLE
LINER SYSTEM : NONE
DRAINAGE SYSTEM : NONE



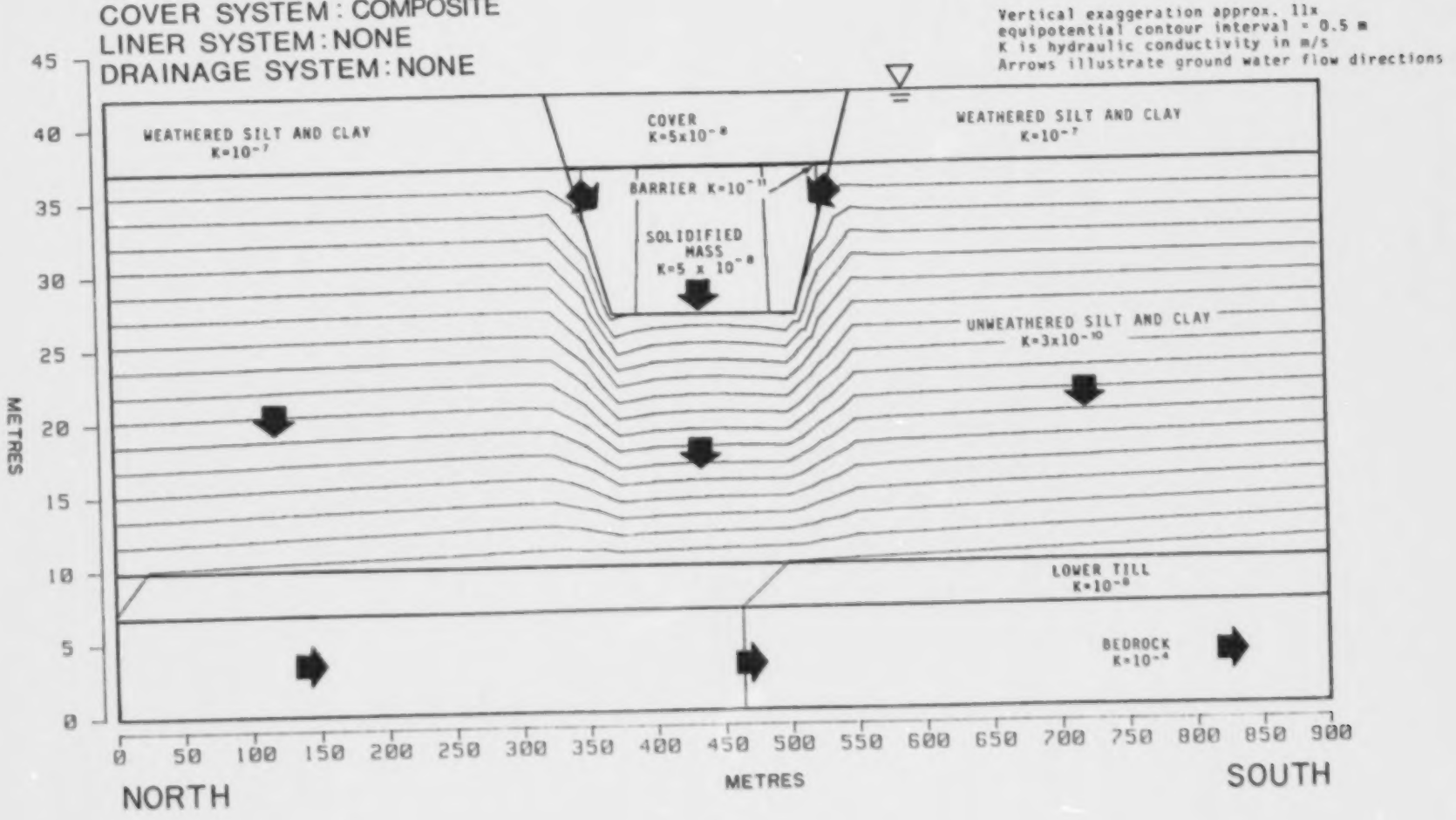
Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

FIGURE 3-4 : SIMPLE LOWER PERMEABILITY COVER EVALUATION
OPERATING MODE: PASSIVE
COVER SYSTEM: SIMPLE
LINER SYSTEM: NONE
DRAINAGE SYSTEM: NONE



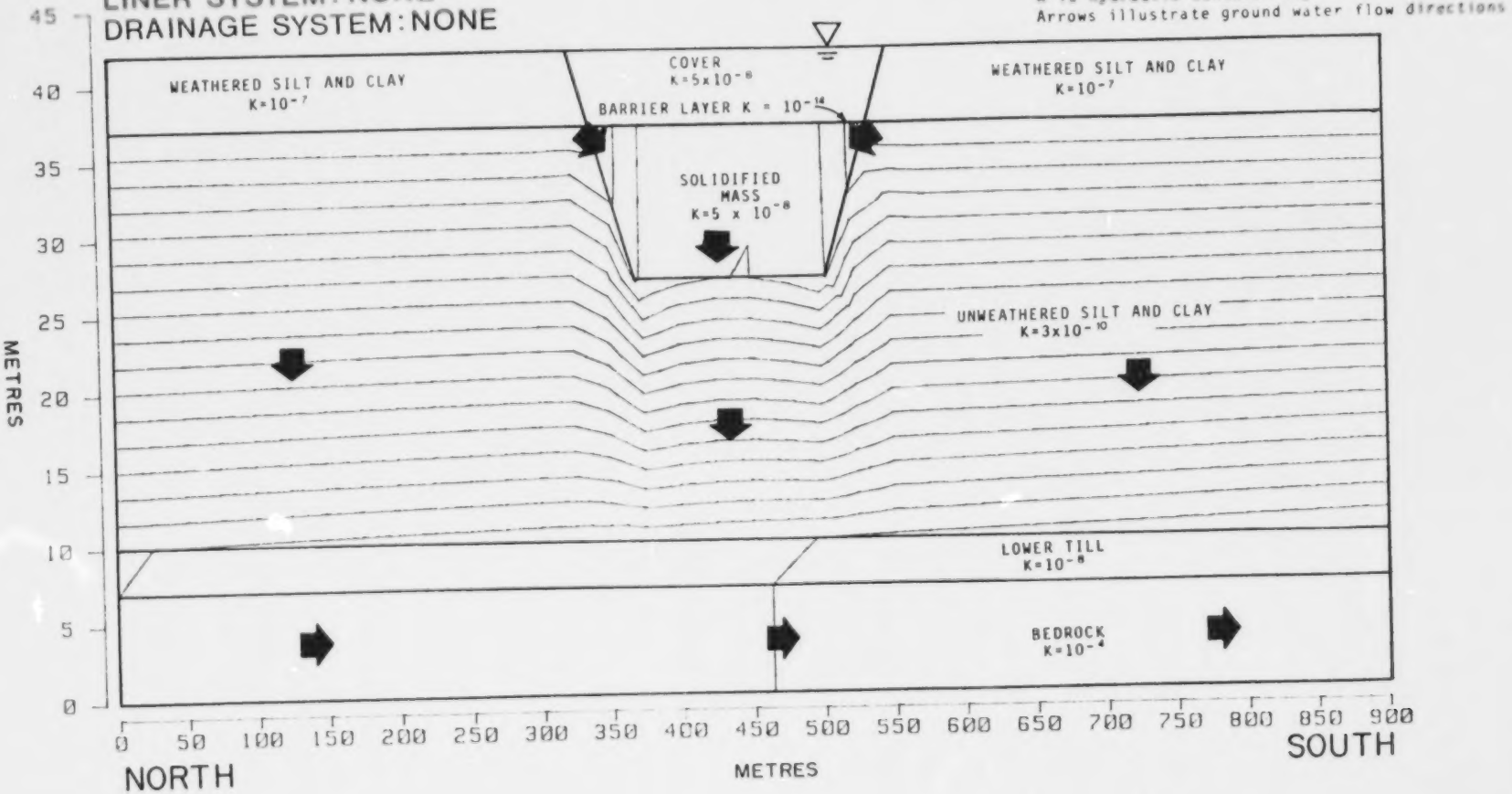
Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

FIGURE 3-5 : COMPOSITE COVER EVALUATION
OPERATING MODE: PASSIVE
COVER SYSTEM : COMPOSITE
LINER SYSTEM: NONE
DRAINAGE SYSTEM: NONE



Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

FIGURE 3-6 : COMPOSITE LOWER PERMEABILITY COVER EVALUATION
OPERATING MODE: PASSIVE
COVER SYSTEM : COMPOSITE
LINER SYSTEM: NONE
DRAINAGE SYSTEM: NONE



Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

landfill is in both vases only marginally reduced relative to the Base Case (about 20% to 30% reduction).

The barrier layers in the base of the cover could play a role in limiting hydrogeologic interaction between the cover and the solidified mass. Upward diffusion of contaminants into the cover could potentially be slowed by the barrier as well. Therefore, barrier layers may provide a potential benefit with respect to minimizing contaminant movement through the surface water and weathered silt and clay pathways. Further research would be required to establish this relationship, however.

Previous "generic" modelling work (GLL 1987a) examined the role of drainage layers in cover systems. It was found that these were of limited benefit for slope angles that would be practical in the shallow entombed concept under gravity drainage conditions. If a cover drainage layer were pumped, infiltration rates through the cover could be kept very low, but there would likely be ground water inflow along the sides of the landfill to offset this.

3.3.3 Liner Systems

(a) Simple Liner Systems

A simple liner system is considered to be excavation, replacement, and recompaction of the native silt and clay material over a certain depth at the base of the landfill. Laboratory and field experience with soils of this type have shown that recompaction is not likely to produce hydraulic conductivity values lower than those of the in situ unweathered silt and clay unless there are significant material inhomogeneities. These would not be expected at the Preferred Site. Therefore, simple liner systems appear to offer little or no benefit relative to having no liner at all.

(b) Composite Liner Systems

Composite liner systems can include single or multiple barriers to minimize seepage of leachate into underlying soils. Overall, the liner must achieve a hydraulic conductivity lower than that of the surrounding native soils to be an effective hydraulic barrier. Two basic types of barriers were identified for consideration in both the liner system and the cover system:

- admixture barrier - addition of bentonite clay to native or imported soil to reduce permeability,

- synthetic membrane barrier - use of fabricated plastic sheets as a low permeability barrier

The following paragraphs introduce the hydrogeologic properties of each type of barrier. This information was obtained through a literature search which included the following research papers: Brown et al., 1983; 1984; Day and Daniel, 1985; Folkes, 1982; Foreman and Daniel, 1984; Gillham et al., 1984; Giroud, 1984; Haxo et al., 1984; Kays, 1977; and Pierce and Peel, 1985.

In a review of available data, Folkes (1982) reported that the hydraulic conductivity values for admixture-type barriers ranged from 1×10^{-8} to 1×10^{-11} m/s based on laboratory tests, and from 1×10^{-8} to 1×10^{-10} m/s based on field testing. The field values would be considered more representative of in-place performance since laboratory testing often excludes the influence of macroscopic (field-scale) inhomogeneities. A review of additional literature did not identify any admixture liner systems with field hydraulic conductivity values lower than 1×10^{-10} m/s. Thicknesses for these liner systems are typically less than 300 mm, though this is considered to be cost-related and thicker liners are technical feasible.

The hydrogeologic properties of synthetic membrane materials must be defined somewhat differently than those of geologic materials. Whereas water is transmitted through pore spaces by advection (flow) due to hydraulic gradients in geologic materials, membranes theoretically contain no void spaces and fluids are transmitted by diffusion due to vapour pressure, osmosis due to chemical gradients, and adsorption due to solubility (Kays, 1977).

In the field, these processes are generally negligible compared to flow through pinholes, seams, rips and other liner imperfections. Therefore, "apparent" field hydraulic conductivity values can be calculated based on the measured leakage rate through large-scale liner sections. Folkes (1982) reports values ranging from about 2×10^{-11} to 2×10^{-13} m/s. Further literature review of synthetic membranes found no values of field hydraulic conductivity lower than 2×10^{-13} m/s.

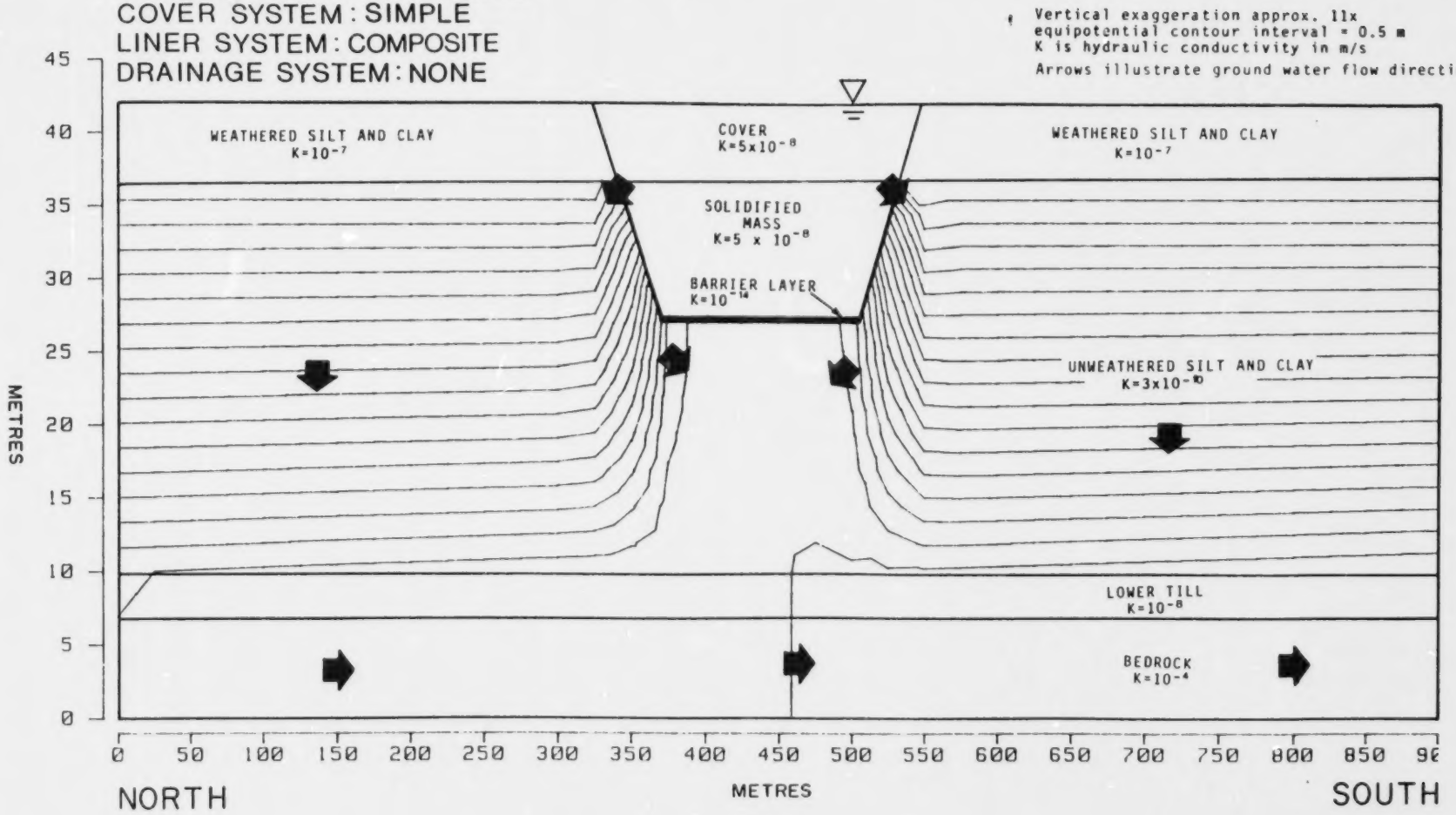
Laboratory testing of synthetic membranes generally concentrates on establishing a "perm rating". This is based on water vapour tests at a constant temperature. Often perm ratings are converted to an "equivalent" hydraulic conductivity value, but the use of these values is limited as the conversion is not exact (Kays 1977). Folkes (1982) reports equivalent hydraulic conductivities based on laboratory testing as low as 7×10^{-16} m/s; this was the lowest value found in the literature review.

Thicknesses of synthetic membrane liners are generally in the range of 0.5 to 2.6 mm (Folkes, 1982). In some cases, however, double liner systems are employed whereby two synthetic membranes are separated by a layer of drainage material.

As a result of the literature review, it was concluded that admixture barrier layers will not provide significantly lower in-place permeability than the native unweathered silt and clay soils. It appears that synthetic membrane barriers may result in lower permeabilities, although the mechanisms by which they transmit ground water are difficult to model. The following modelling results represent the liner as a 0.5 m thick barrier with a hydraulic conductivity of 1×10^{-14} m/s. While this may not truly represent the exact functioning of any specific liner, it does provide a general indication of how a low permeability barrier affects ground water flow in and around the landfill.

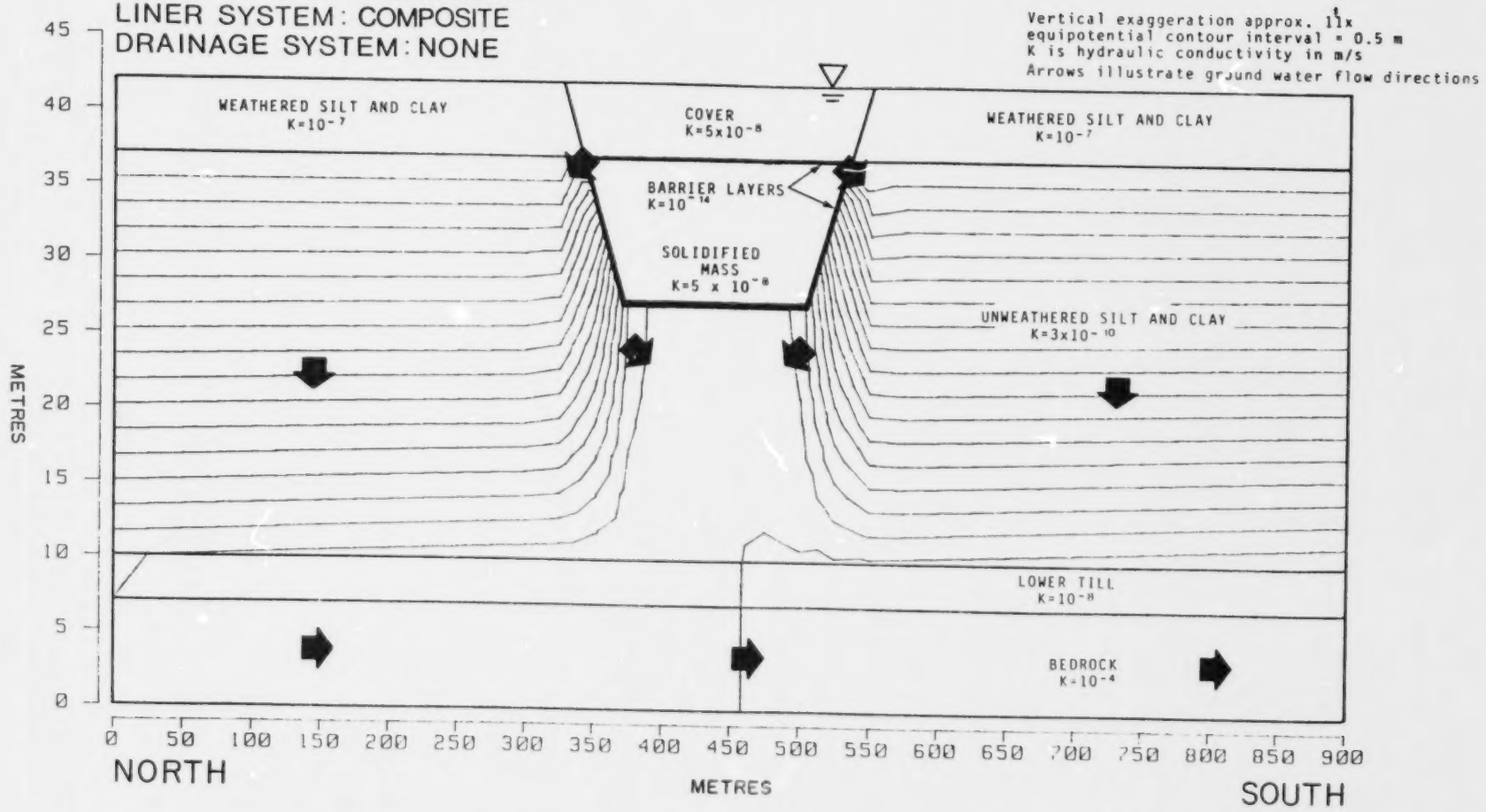
Figure 3-7 demonstrates the effect of including a low hydraulic conductivity barrier layer in the liner system (bottom and slide slopes) in the passive mode. In effect, the barrier restricts ground water flow through the landfill and the result is a low rate of leachate discharge from the base of the landfill relative to the Base Case. Infiltration rates through the cover are correspondingly low as well.

FIGURE 3-7 : COMPOSITE LINER EVALUATION
OPERATING MODE: PASSIVE
COVER SYSTEM : SIMPLE
LINER SYSTEM : COMPOSITE
DRAINAGE SYSTEM : NONE



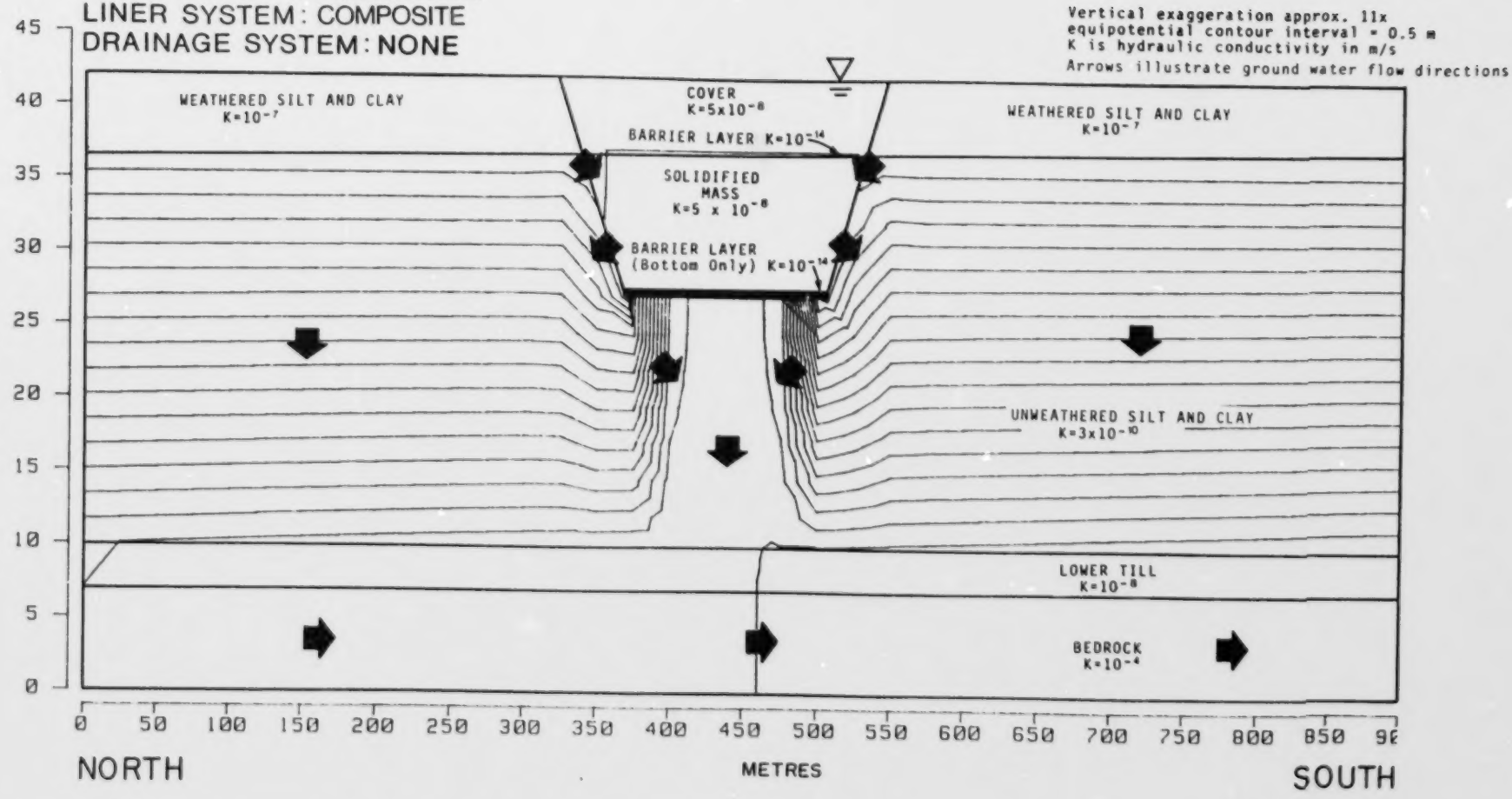
Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

FIGURE 3-8 : COMPOSITE LINER AND COVER EVALUATION
OPERATING MODE: PASSIVE
COVER SYSTEM : COMPOSITE
LINER SYSTEM : COMPOSITE
DRAINAGE SYSTEM : NONE



Note: Shallow surficial ground water flow not shown, see GLAL, 1986t

FIGURE 3-9 : COMPOSITE LINER EVALUATION - BASE ONLY
OPERATING MODE: PASSIVE
COVER SYSTEM: COMPOSITE
LINER SYSTEM: COMPOSITE
DRAINAGE SYSTEM: NONE



Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

Figure 3-8 illustrates that the addition of a barrier layer in the cover in conjunction with the barrier layer in the liner has very little additional benefit with respect to ground water flow in comparison with Figure 3-7. However, the cover barrier layer may reduce potential impacts on the surface water and weathered silt and clay pathways as noted in Section 3.3.2.

Figure 3-9 simulates the effect of having a barrier layer in the cover and base of the landfill only. This could represent a situation where the barrier layer could not be constructed on the side slopes, for instance. Under these conditions, in a passive operational mode, flow from the base of the landfill is restricted, but there appears to be a component of flow that enters and exists the landfill along the sides. This is therefore less desirable than a barrier layer on both the landfill base and on the side slopes.

In an active operational mode, which was modelled in the earlier "generic" work (GLL 1987a), barrier layers in the composite liner system tend to minimize any outflow from between drains. Barrier layers also tend to minimize the inflow of ground water from the surrounding native soils into the drainage system. This is further considered in the following discussion regarding drainage systems.

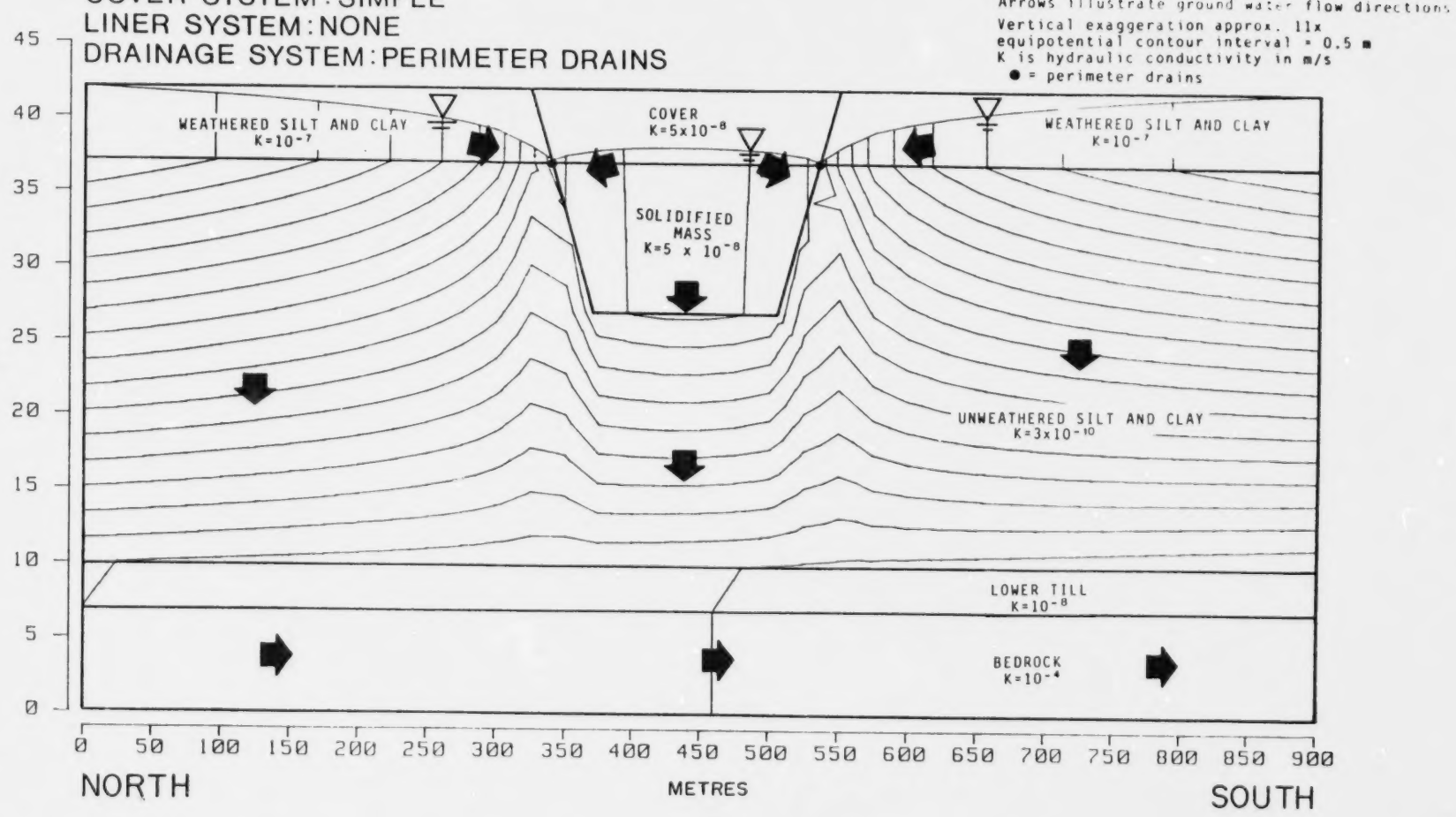
3.3.4 Drainage Systems

(a) Perimeter Drains

Figures 3-10 and 3-11 depict the effect that perimeter drains have when they are used in an active operational mode. In both cases, infiltration to the landfill is controlled by the drains, and the rate of downward ground water flow beneath the landfill is about 20% to 30% lower than in the surrounding undeveloped areas. Figure 3-11 shows that a cover barrier layer used in conjunction with the perimeter drains is somewhat more effective than a simple cover system.

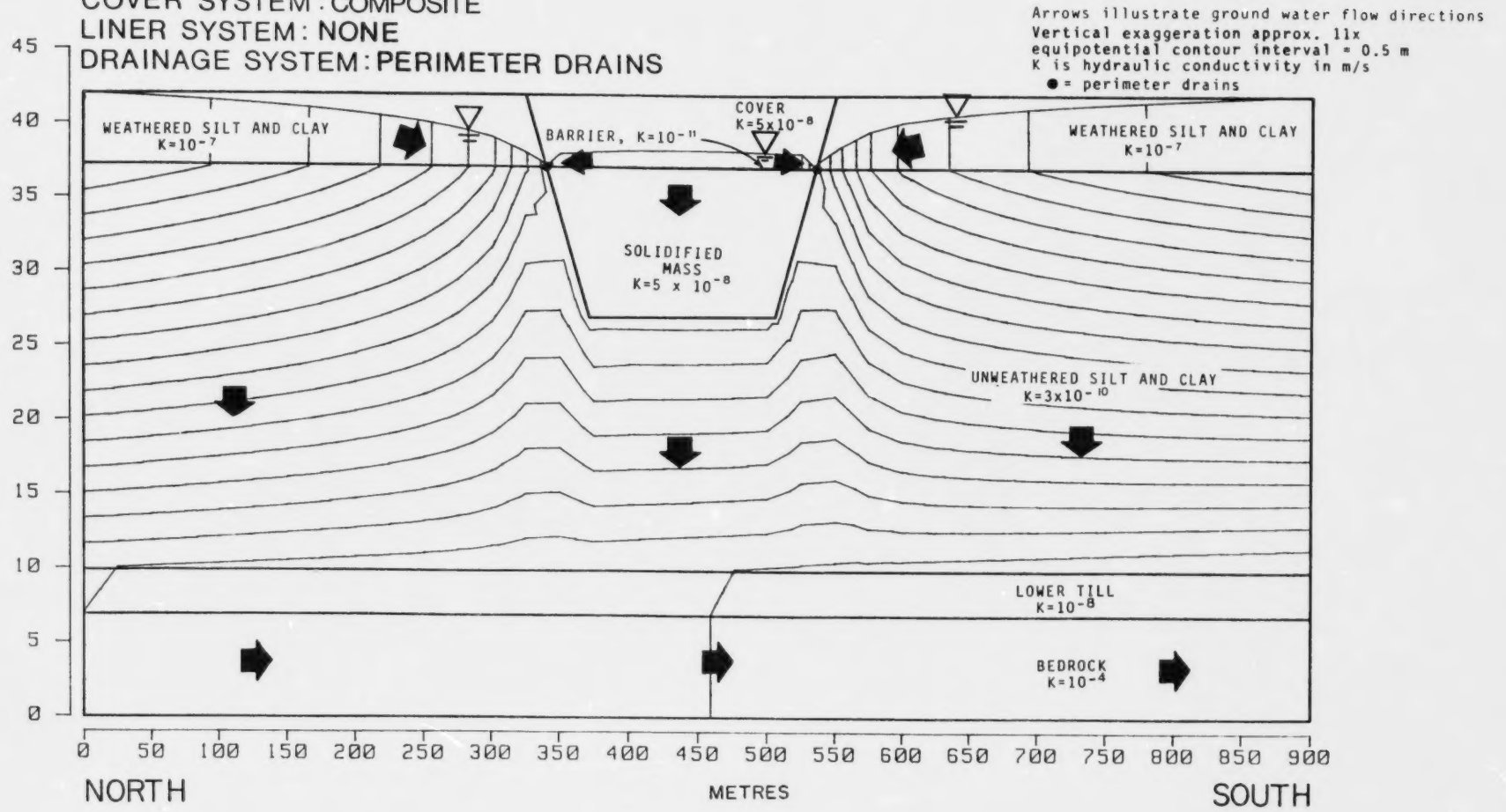
Perimeter drains are especially useful in controlling the weathered silt and clay pathway. With sufficient drainage capacity, gradients toward the drains can be maintained that will limit leachate flow away from the landfill in the weathered silt and clay.

FIGURE 3-10 : PERIMETER DRAINS EVALUATION
OPERATING MODE: ACTIVE
COVER SYSTEM: SIMPLE
LINER SYSTEM: NONE
DRAINAGE SYSTEM: PERIMETER DRAINS



Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

FIGURE 3-11 : PERIMETER DRAINS AND COMPOSITE COVER EVALUATION
OPERATING MODE: ACTIVE
COVER SYSTEM : COMPOSITE
LINER SYSTEM : NONE
DRAINAGE SYSTEM : PERIMETER DRAINS



Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

(b) Underdrains

An underdrain system generally consists of a highly permeable granular layer or synthetic drainage net at the bottom and sides of the landfill. Drainage can be accomplished by pumping from a piping system installed within the granular layer or from a sump that is fed from the underdrain system. These systems, operated actively, can be very effective in controlling leachate produced in the landfill. Based on earlier "generic" modelling (GLL 1987a), pumping from drainage points appropriately spaced will result in complete control of the water table elevation in the landfill. This in turn controls the hydraulic gradient in the native silt and clay beneath the landfill. For instance, if the landfill were fully drained, a net upward gradient would result that would cause ground water flow to be inwards to the landfill. Contaminant migration to the bedrock aquifer would be as a result of diffusion processes only. An optimum pumping rate might be considered that maintains a net zero gradient beneath the landfill.

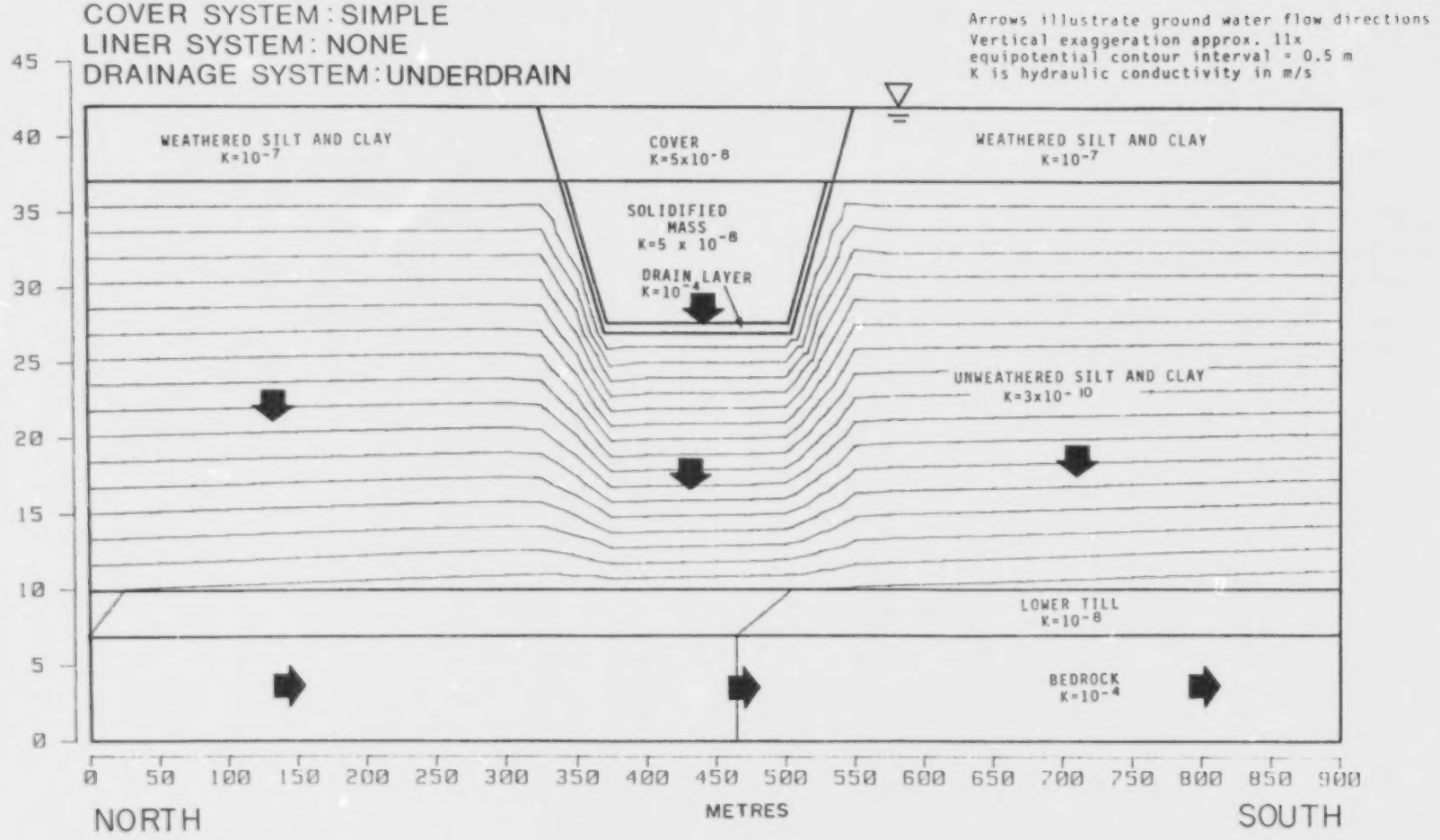
In an active operational mode, where an underdrain system is included and operated, composite liner and cover systems will tend to reduce the quantity of ground water inflow from beneath the landfill into the drainage system and hence reduce the treatment requirements. However, this might be considered an adverse effect if it limited the potential to recover contaminants that existed beneath the base of the landfill.

Figures 3-12 and 3-13 illustrate the effects of underdrain systems in a passive operational mode (Figure 3-13 includes a passive drainage layer in the base of the cover as well). These drainage systems have little beneficial or detrimental effect on ground water flow when they are not operational, as comparison with ground water flow for the Base Case (Figure 3-2) shows.

3.3.5 Summary

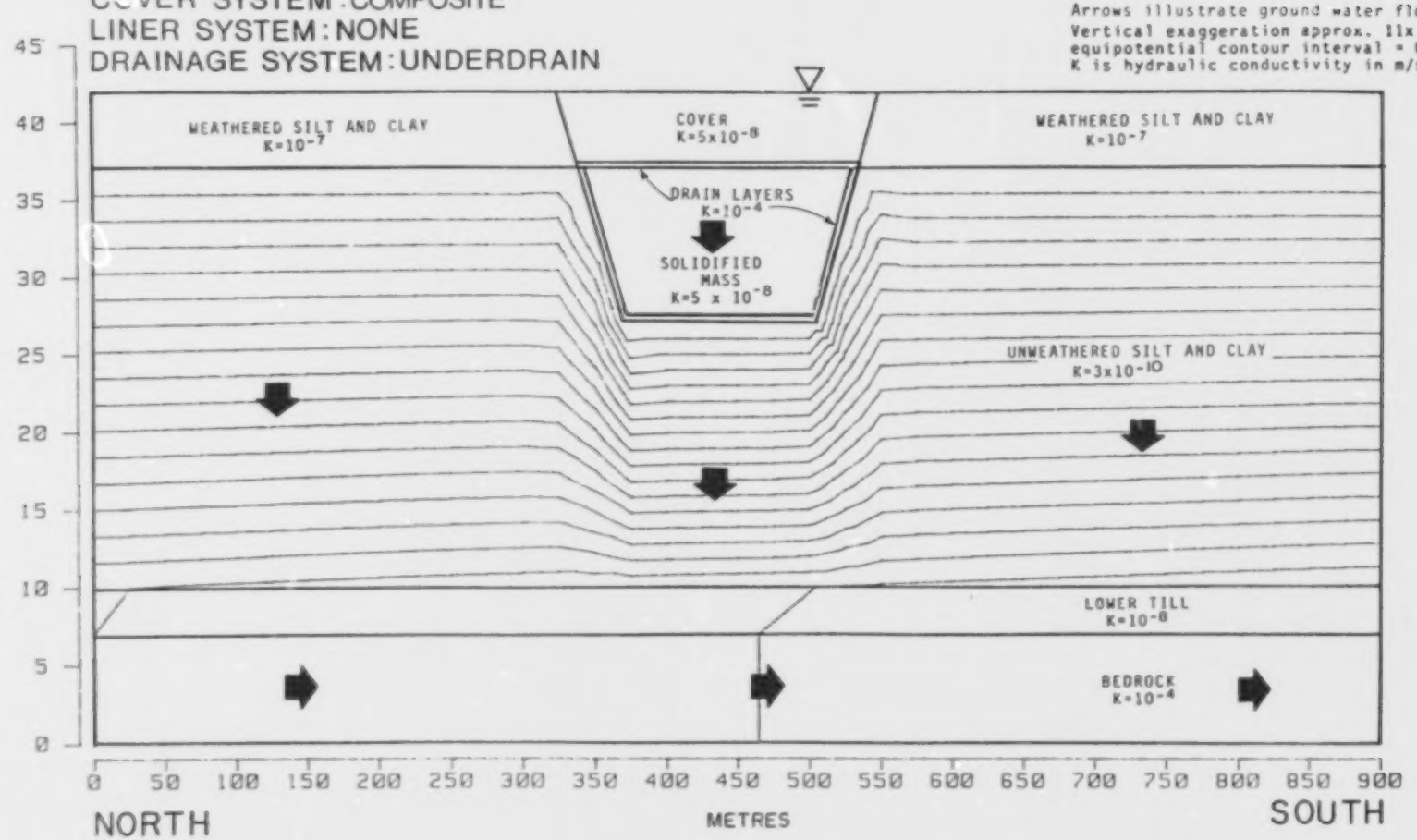
Certain conclusions regarding the hydrogeologic performance of landfill engineered devices, or combinations of devices, are evident from the preceding discussions. These are summarized below, with all comparisons relative to the Base Case (no liner, no drainage system, simple cover):

FIGURE 3-12 : PASSIVE UNDERDRAIN EVALUATION
OPERATING MODE: PASSIVE
COVER SYSTEM: SIMPLE
LINER SYSTEM: NONE
DRAINAGE SYSTEM: UNDERDRAIN



Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

FIGURE 3-13 : PASSIVE UNDERDRAIN AND COVER UNDERDRAIN EVALUATION
OPERATING MODE: PASSIVE
COVER SYSTEM: COMPOSITE
LINER SYSTEM: NONE
DRAINAGE SYSTEM: UNDERDRAIN



Note: Shallow surficial ground water flow not shown, see GLAL, 1986b

- Simple liner systems (recompacted clay) offer no performance benefits.

- None of the devices are detrimental to performance in the passive operational mode (or after failure).

- Composite liner systems must achieve an overall hydraulic conductivity less than that of the native unweathered silt and clay to provide a benefit in reducing leachate release. Admixture barriers do not appear capable of meeting this requirement. Synthetic membrane barriers may be capable of meeting this requirement although it is difficult to predict their in situ hydrogeologic performance.

- Composite cover systems, by themselves, provide minimal additional protection to the aquifer in the passive mode but may offer protection of the surface water and weathered silt and clay, and reduce leachate collection and treatment requirements in the active operational mode.

- Weathering of the simple cover system resulting in increased hydraulic conductivity will not significantly increase infiltration and leachate generation in a passive operational mode.

- Drainage layers in the cover system will not likely provide a substantial benefit for the shallow entombed landfill concept in the passive mode; in the active mode they may reduce leachate collection and treatment requirements.

- Perimeter drains offer some control of the surface water and weathered zone pathways, and marginally improved control of ground water flow to the aquifer from beneath the landfill.

These conclusions, in conjunction with the preliminary engineering analysis, resulted in the establishment of several systems of landfill devices that were considered in the

detailed comparative evaluation. The systems are documented in the Landfill PAR (M. M. Dillon, 1986) and consist of the following:

BASE CASE:
- simple cover
- no liner
- no drainage system (passive mode)

SYSTEM 1: (includes non-repairable devices)
- composite cover
- composite liner
- underdrain system (active mode)

SYSTEM 2: (includes non-repairable devices)
- simple cover
- no liner
- underdrain system (active mode)

SYSTEM 3: (repairable/replaceable devices)
- simple cover
- no liner
- perimeter drains (active mode)

The following section presents the detailed hydrogeologic comparative evaluation of these systems of engineered devices.

3.4 COMPARISON OF SYSTEMS OF ENGINEERED DEVICES

Figure 3-14 shows a summary of the comparative hydrogeologic evaluation of the systems of engineered devices. The following presents the rationale for the ratings within each of the sub-criterion that are shown in Figure 3-14.

3.4.1 Short-term Performance

Short-term performance is considered to represent the period of time in which engineering devices are fully functional and are being operated as per their design.

FIGURE 3-14 COMPARATIVE HYDROGEOLOGIC EVALUATION OF SYSTEMS OF DEVICES

CRITERIA	SUB-CRITERIA	BASE CASE - simple cover - no liner - no drainage system (passive mode)	SYSTEM 1 -composite cover -composite liner - underdrain system (active mode)	SYSTEM 2 - simple cover - no liner - underdrain system (active mode)	SYSTEM 3 - simple cover - no liner - perimeter drains (active mode)
SHORT-TERM PERFORMANCE	• RATE OF CONTAMINANT TRANSPORT TO AQUIFER	LOW	LOWEST*	LOWEST*	LOWER
	• RATE OF CONTAMINANT TRANSPORT TO SURFACE	LOW	LOWER*	LOWER*	LOWER*
	• RATE OF CONTAMINANT TRANSPORT IN WEATHERED SILT AND CLAY	LOW	LOWER*	LOWER*	LOWER*
LONG-TERM PERFORMANCE (NON-REPAIRABLE DEVICES FAILURE)	• RATE OF CONTAMINANT TRANSPORT TO AQUIFER	LOW	LOW	LOW	LOWER*
	• RATE OF CONTAMINANT TRANSPORT TO SURFACE	LOW	LOW	LOW	LOWER*
	• RATE OF CONTAMINANT TRANSPORT IN WEATHERED SILT AND CLAY	LOW	LOW	LOW	LOWER*

* Indicates best rating for sub-criterion.

Basis for comparison: - shallow entombed landfill concept

- cell development method

Consideration regarding the life expectancy of these devices is contained in the Landfill PAR (M.M. Dillon 1986). The following is a discussion of each sub-criterion.

Rate of contaminant transport to aquifer.

The Base Case, the most basic of all of the systems, produces a low rate of contaminant transport to the underlying aquifer. This can be credited in part to the shallow entombed concept which limits the hydraulic head (i.e. ground water mound) over the landfill since it is finished almost level with the surrounding grade. The other key factor is the low hydraulic conductivity of the native silt and clay soils at the Preferred Site that results in low rates of ground water flow out of the base of the landfill.

System 3 provides further reductions in the contaminant transport rate to the aquifer since the perimeter drains can be utilized to lower the water table above the landfill, resulting in lower rates of leachate discharge from the base.

System 1 and System 2 both result in the lowest rate of contaminant transport to the aquifer in the short-term. The underdrain systems can be operated such that a net zero or net inward hydraulic gradient to the landfill will be achieved. As a consequence, contaminant transport beneath the landfill will occur by the process of diffusion alone, which is slower than diffusion and advection (flow) acting together as for the other two systems.

Potentially, System 1 could produce lower rates of contaminant transport than System 2 if the barrier layers in the liner system (e.g. synthetic membranes) result in slower diffusion rates than the native clays. However, this would require further detailed study to confirm; therefore, System 1 and System 2 are ranked equally in this comparison.

Rates of contaminant transport to surface.

The shallow ground water flow and surface water flows are anticipated to interact closely at the Preferred Site (GLL 1987b). This is reflected in the ridge and swale drainage network prevalent at the site. The following considers the potential for contaminants to be introduced into the surface water system via shallow ground water flow in the weathered silt and clay.

The Base Case is considered to result in a low rate of contaminant transport to surface. The simple cover system is constructed to approximately recreate prefacility topographic conditions. The shallow entombed concept buries all of the solidified mass beneath the base of the weathered silt and clay, which is thought to be the lower limit of shallow flow. Therefore, shallow flow should also be limited to the upper portion of the silt and clay cover in the short- and long-term. Under these conditions, contaminants should only interact with shallow flow by upward diffusion from the solidified mass, which is a slow process capable of transporting only small quantities of contaminants relative to the dilution available in the surface water system.

System 1, System 2 and System 3 potentially provide lower rates of contaminant transport to the surface since all three have operating drainage systems. These drainage systems will tend to maintain greater downward or lateral gradients in the cover system and therefore limit the amount of infiltration that can return to surface. Upward diffusion would be the main process by which contaminants are transported to surface under these conditions. If the barrier layer in the composite cover of System 1 were proven to act as a diffusion barrier, then this system would be ranked lowest for this sub-criterion, although this is not currently reflected in the ranking.

Rate of contaminant transport in weathered zone.

There is a potential (though considered limited) that contaminants could be transported laterally to shallow off-site receptors in the weathered silt and clay such as bored wells or surface water. This potential is considered to be low for the Base Case because ground water cannot mound above grade in the shallow entombed landfill, limiting the formation of significant distance in the weathered silt and clay are not expected because the site is topographically flat.

System 1, System 2 and System 3 each have actively operated drainage systems that would tend to produce gradients toward the landfill. Therefore these three systems are ranked lower than the Base Case in terms of rate of contaminant transport in the weathered silt and clay.

3.4.2 Long-Term Performance

Long-term performance represents the time after the failure of any non-repairable devices. Information regarding the life expectancy of engineered devices is provided in the Landfill PAR (M.M. Dillon 1986). Leachate is expected to be produced long after these devices fail. The Base Case will continue to behave in a fashion similar to the short-term since it is passively operated and contains no devices that are subject to failure. Hence the above discussion for the Base Case performance applies here as well. Similarly, System 3 contains repairable/replaceable devices, and assuming that the perimeter drains are maintained and operated in the long-term, the ranking and discussion for the short-term performance of this system applies.

The liner and underdrain of System 1, and the underdrain of System 2 are non-repairable devices which can be assumed to fail in the long-term. Consequently, long term performance of both systems is equivalent to the Base Case, and the long-term performance rankings for System 1 and System 2 are the same. The previous discussion of the long-term performance of System 1 and System 2.

3.5 RECOMMENDATIONS

System 1 and System 2 are expected to be equal in terms of their short-term hydrogeologic performance (Figure 3-14). In the long-term System 3 will likely outperform these two systems from a hydrogeologic performance standpoint, assuming that its repairable/replaceable engineered devices are maintained.

When the engineering-related criteria are also considered in the comparative evaluation, System 2 achieves the best overall rating. This is documented in the Landfill PAR (M.M. Dillon 1986). One basis for this selection is that the perimeter drains of System 3 could be installed at any future date should the underdrains of System 2 fail. This solution has the benefits of combining the maximum short-term performance of System 2 with the long-term performance of System 3.

System 2, which is composed of a simple cover system, underdrain system, and no liner (native clay base), was identified as the preferred option for conceptual engineering design of the shallow entombed landfill.

4.0 LANDFILL OPERATIONAL MODE

4.1 INTRODUCTION

Two operational modes were considered for the conceptual design of the shallow entombed landfill;

- active mode - underdrain system in place and actively collecting leachate
- passive mode - no underdrain, or underdrain in place but not operated.

Note that in the later option, the underdrain may be installed for use only as a contingency and/or for monitoring purposes.

4.2 COMPARISON OF OPERATIONAL MODES

Figure 4-1 lists the relative advantages and disadvantages of the passive and active modes for the shallow entombed landfill concept and the System 2 combination of engineered devices.

4.3 RECOMMENDATIONS

The passive mode was recommended based on hydrogeologic considerations for conceptual facilities design, with the understanding that the leachate collection system be installed for monitoring and contingency purposes.

FIGURE 4-1 COMPARISON OF ACTIVE AND PASSIVE OPERATIONAL MODES

Active Mode	Passive Mode
• maximum short-term performance	• lower short term performance but equal long term performance
• ongoing maintenance, energy inputs, and leachate treatment cost and commitments	• minimal maintenance, energy input and leachate treatment
• potential to artificially speed up natural decay of contaminants in short-term but more difficult to assess long-term leachate quality	• leaching at natural rates, should allow assessment of long term leachate quality
• underdrain system has finite lifespan; difficult to repair, non-replaceable	• use of underdrain only for monitoring and contingency will maximize its effective lifespan
• persistent (untreatable) contaminants will be recycled to the landfill indefinitely	• the natural environment will attenuate contaminants from the beginning which can be monitored in the early stages

5.0 LANDFILL DEVELOPMENT METHOD

5.1 INTRODUCTION

Three development methods were considered for the conceptual design of the shallow entombed landfill:

- cell development - discrete excavations of about 100 m x 150 m in area
- trench development - excavations of about 100 m in width but extending from about 250 m to 720 m in length
- area development - excavations that cover all available landfill area in a continuous fashion.

These development methods are described in further detail, including drawings, in the Landfill PAR (M.M. Dillon 1986). The following section considers the hydrogeologic aspects of these development methods.

5.2 COMPARISON OF DEVELOPMENT METHODS

The three development methods were qualitatively evaluated with respect to hydrogeologic performance. This information was provided as input to the comparative evaluation described in the Landfill PAR (M.M. Dillon 1986).

The area development method increases the total volume of solidified mass (and therefore the total mass of contaminants) in the landfill compared to the cell development method, assuming a fixed land area is utilized for landfilling on the site. The trench development method is intermediate between these two.

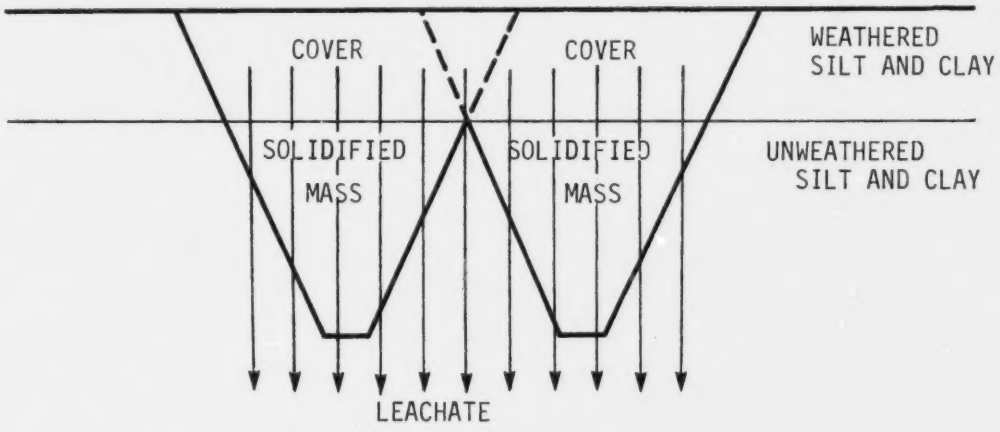
Figure 5-1 shows that there would be little difference expected in ground water quality beneath the site for the three development methods. The key assumptions in this

FIGURE 5-1

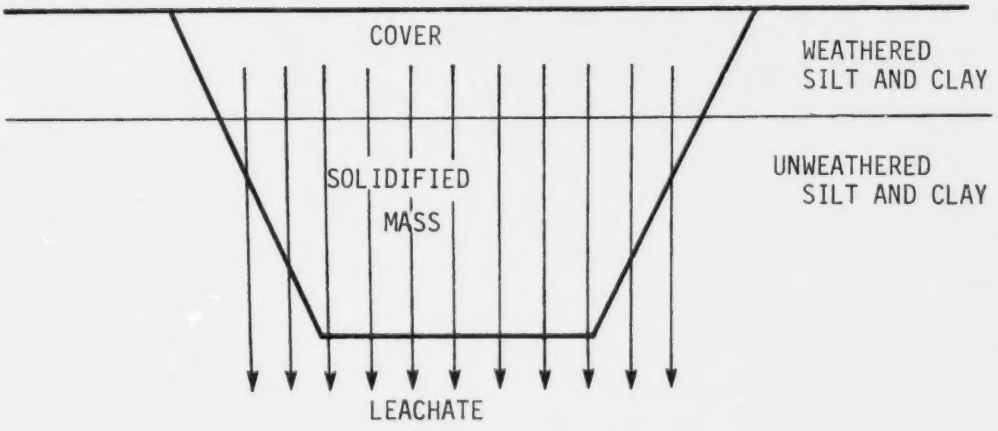
COMPARISON OF DEVELOPMENT METHODS - GROUND WATER QUALITY

A) CELL / TRENCH DEVELOPMENT METHOD

NOT TO SCALE



B) AREA DEVELOPMENT METHOD



ASSUMPTIONS: (1) Tightest possible packing of cells/trenches (optimization)
(2) Vertically downward ground water flow
(3) Contaminants leached at solubility limits
(4) Conservative contaminant (no attenuation)
(5) Passive shallow entombed landfill

Gartner Lee Limited

assessment is that the layout of the cells or trenches could be optimized to provide the greatest density per available area in order to maximize site life and capacity. This optimization is not considered in the landfill PAR, but would have been had cell or trench development been selected as the preferred method (M.M. Dillon, personal communications). Other assumptions are presented in Figure 5-1.

The real difference among the three development methods is with respect to total contaminant loading to the aquifer. Although Figure 5-1 illustrates that the rate and concentration of contaminant transport is approximately equivalent in the early years, the extra contaminant mass contained in the area method would extend the time frame over which leachate would be produced relative to the cell method (the trench method is again intermediate).

Figure 5-2 shows GLL's input to the comparative evaluation. Consistent with the above discussion, the rate of contaminant transport in all cases, both short-term and long-term, has been ranked as low. Since the total length of time and total contaminant loading do not affect the factors used to assess impact (e.g., contaminant concentration at the property boundary), the distinction between the three development methods discussed in the preceding paragraph is not reflected in the comparative evaluation.

Contaminant transport in the shallow ground water, affecting both the weathered zone and surface water pathways, is not expected to be influenced by the choice of development method.

5.3 RECOMMENDATION

No clear preference for the cell, trench, or area landfill development methods was identified based on hydrogeologic performance criteria. Thus, the three options were ranked equally in the comparative evaluation presented in the Landfill PAR (M.M. Dillon 1986). When the engineering considerations are included, the area development method is preferred, principally due to cost-capacity advantages. Thus, the area development method has been selected as the basis for further conceptual landfill design.

FIGURE 5-2 COMPARATIVE HYDROGEOLOGIC EVALUATION OF DEVELOPMENT METHODS

CRITERIA	SUB-CRITERIA	CELL	TRENCH	AREA
SHORT-TERM PERFORMANCE	• RATE OF CONTAMINANT TRANSPORT TO AQUIFER	LOW	LOW	LOW
	• RATE OF CONTAMINANT TRANSPORT IN SURFACE	LOW	LOW	LOW
	• RATE OF CONTAMINANT TRANSPORT IN WEATHERED ZONE	LOW	LOW	LOW
LONG-TERM PERFORMANCE (NON-REPAIRABLE DEVICES FAILURE)	• RATE OF CONTAMINANT TRANSPORT TO AQUIFER	LOW	LOW	LOW
	• RATE OF CONTAMINANT TRANSPORT TO SURFACE	LOW	LOW	LOW
	• RATE OF CONTAMINANT TRANSPORT IN WEATHERED ZONE	LOW	LOW	LOW

Basis for comparison:
- shallow entombed landfill concept
- simple cover
- no liner (native clay base)
- inactive underdrain layer (passive operational mode)

6.0 OTHER HYDROGEOLOGIC INPUTS TO ENGINEERING DESIGN

6.1 EXCESS CLAY STOCKPILES

The landfill excavation will produce large quantities of excess silt and clay soils. Ultimate disposal of these soils will not be on or in the immediate vicinity of the landfill; however, consideration has been given to temporarily stockpiling excess silt and clay in the landfilling area in order to ensure proper distribution of off-site transport (M.M. Dillon 1986). Gartner Lee Limited (GLL) examined the hydrogeologic implications of the excess clay stockpiles.

It is estimated that the stockpiles would become saturated during their proposed existence of over 20 years. The rise in the local water table into the stockpile would result in an increased hydraulic gradient in the silt and clay soils overlying the bedrock aquifer. The gradient increase could be as much as 50% for the case where stockpiles are located on undeveloped land, and as much as 90% where stockpiles are above completed landfill areas.

It is known that the transmission of hydraulic gradient changes to depth is delayed in fine-textured soils. Therefore, event after a stockpile is removed from undeveloped land, increased gradients may still exist for some period of time after the landfill is constructed.

Increased hydraulic gradients beneath the landfill imply that ground water, which may contain leached contaminants, will move downward at correspondingly greater rates. The impact of the additional contaminant loading on the aquifer may prove to be unacceptable.

It is therefore recommended that excess clay stockpiles be eliminated where possible. If they are considered necessary in some instances, then they should be constructed such that they minimize the hydrogeologic impacts to the extent possible. This can be considered during the detailed design stage. As well, the geotechnical concerns regarding excess clay stockpiles will require detailed assessment prior to construction (GLL, 1987c).

6.2 SURFACE WATER DRAINAGE DESIGN

6.2.1 Introduction

The final profile of the shallow entombed landfill concept will provide a 5 m thick (approximately) cover of recompacted native silt and clay materials. The surface of the cover will require topographic grading in order to promote positive surface water control. Several alternatives for final cover grading were developed by M.M. Dillon Ltd. and are presented in the Landfill PAR (M.M. Dillon 1986). Briefly, the alternatives are:

Base Case
- final cover topography simulates natural site relief
- 2% grades
- drainage divide ridges at 100 m spacing
- 1 m maximum relief

Case 1
- 4% grades
- single drainage divide at landfill centre
- average crest height 4.5 m; maximum crest height 5.6 m

Case 2
- 4% grades
- two drainage divides per landfill area
- central collector ditch per landfill area
- average crest height 2.25 m; maximum crest height 1.4 m.

6.2.2 Assumptions

The following assumptions were incorporated into the assessment:

- shallow entombed landfill concept
- simple cover construction (i.e., recompacted native soils)

- native clay base (no liner)
- underdrain layer
- area development method
- passive operational mode

Although the passive operational mode is assumed, comments are also provided with respect to the active operational mode, should it be required as a contingency.

6.2.3 Methodology

A comparative evaluation procedure was used that was similar to that described in Chapter 2.0 for the selection of landfill concept. Again, GLL's input was in regard to the performance criteria, in particular, hydrogeologic performance.

6.2.4 Results

Figure 6-1 shows the rankings for each sub-criterion. The rationale for the ratings are presented in this section for each alternative.

Two hydrogeologic pathways have been considered: shallow ground water flow in the weathered zone, and deeper flow to the underlying bedrock aquifer. The rate of flow in each of these pathways reflects the rate at which contaminants will be transported. The concepts are discussed in the order of their hydrogeologic preference.

Base Case

This concept most closely resembles the natural site conditions, which is the basis on which the shallow entombed landfill concept was recommended. It is rated as having the lowest impacts in the passive operational mode.

During wet periods (i.e., rainfall, snow melt etc.), the ground water table is expected to rise nearly to surface. However, between recharge events the water table is expected to fall to the level of the bottom of the swales or lower and become reasonably flat due to the relatively close spacing and low overall relief of this concept.

FIGURE 6-1 COMPARATIVE HYDROGEOLOGIC EVALUATION OF COVER SURFACE GRADING METHODS

CRITERIA	SUB-CRITERIA	BASE CASE	CASE 1	CASE 2	CASE 3
HYDROGEOLOGIC PERFORMANCE	Impact on Aquifer - Passive Mode	LOW*	HIGH	INTERMEDIATE	INTERMEDIATE
	Impact on Weathered Zone - Passive Mode	LOW*	HIGH	INTERMEDIATE	INTERMEDIATE
	Impact on Aquifer - Active Mode	LOW*	LOW*	LOW*	LOW*
	Impact on Weathered Zone - Active Mode	LOW*	LOW*	LOW*	LOW*

*Indicates best rating for sub-criteria.

In either case, ground water flow to the aquifer will be consistent and only slightly greater than natural conditions (due to the burial of the higher permeability solidified mass).

Case 1

Case 1 has the greatest overall relief of all of the alternatives, hence will produce the highest water table level (mound) during recharge. The result will be an increase in the overall hydraulic gradient between surface and the bedrock aquifer, and increased rates of contaminant transport in this pathway by up to 45% compared to the Base Case. The mounding also produces a greater probability for interaction between shallow flow in the weathered zone and the underlying solidified mass, since the additional hydraulic head may tend to drive shallow flow to deeper depths.

Greater overall relief also suggests that the water table mounding formed during recharge periods will take longer to dissipate during drier periods. This tends to accentuate the impacts noted above by stretching out the time over which they occur.

For the reasons discussed above, Case 1 was rated as causing the greatest impacts in the passive operational mode.

Case 2; Case 3

Case 2 and Case 3 have overall topographic relief intermediate between those of the Base Case and Case 1. Thus, their hydrogeologic performance is also intermediate. Some water table mounding is predicted for these alternatives, which will increase contaminant transport rates to the bedrock aquifer by up to 14% and 10% respectively. Similar increases in shallow flow/solidified mass interaction would also be expected.

These two alternatives will also be slightly better than Case 1 in reducing the time span of residual mounding because the spacing between discharge ditches is closer. Therefore, peak impacts will occur over a shorter duration.

6.2.5 Summary and Discussion

It is apparent from the results that optimum hydrogeologic performance is obtained for final covers when:

(1) overall topographic relief is minimized, and,

(2) distance between discharge points (swales or ditches) is minimized.

The drainage slopes appear to be important only as they relate to the above two goals.

The analysis presented previously has assumed passive operational mode. In the active operational mode the order of preference for the concepts may be somewhat different.

Assuming that the pumping rate in the underdrain system is sufficient to maintain a water table well below surface, then the amount of infiltration may be limited only by physical hydrologic processes. Under these conditions, the cover concept that promotes maximum runoff, and therefore minimum infiltration, would be preferred from the standpoint of minimizing the quantity of leachate to be collected by the underdrain system for treatment. However, in all cases the weathered zone and bedrock aquifer contaminant pathways will be well protected in the active mode, hence each alternative is rated as having low impacts in Figure 6-1.

6.3 LANDFILL DETENTION POND DESIGN

The conceptual design of the OWMC landfill includes a storm detention pond, presently proposed for the southeastern corner of the site (M.M. Dillon, 1986). OWMC identified two hydrogeologic issues related to the size and location of the proposed storm detention pond. These issues are discussed below.

(1) Impact of the pond (short-term and usually dry) on the landfill.

Significant hydrogeologic impacts are not anticipated as a result of the range of pond sizes currently under consideration. The total pond depth is assumed to be 3 m below grade, within the most fractured portion of the weathered zone, which is not being relied upon to provide containment of potential contaminants. The base of the pond

may have to be recompacted in order to prevent excessive seepage losses into the more permeable weathered zone.

(2) Pond placement

It is important to determine if the pond could be placed over a completed landfill area in the last few years of operation to gain extra landfill capacity. Based on a qualitative assessment, this appears to be technically feasible. However, the final decision should be made during the later years of the operations. At that time, performance monitoring data from the early operational years can be assessed to confirm the feasibility. In fact, the performance monitoring for the area of the proposed relocation could be specially designed for this purpose.

If the pond is to be placed over the completed landfill, a liner should be considered to minimize potential interactions between the pond and the landfill. In this case as well, the decision could be taken based on performance monitoring results from the early operational years, as well as performance data from the original pond.

6.4 LEACHATE QUANTITIES

6.4.1 Introduction

Although the proposed operational mode for the shallow entombed landfill is passive, it is necessary to estimate the potential quantities of leachate produced in the active operational mode in order to evaluate the design of the leachate collection and transmission system (M.M. Dillon 1986). The quantity of leachate collected by the underdrain will be a direct function of the quantity of infiltration at the landfill surface and the efficiency of the underdrain. In order for the underdrain to be efficient, it must be operated such that the water table within the landfill is lower than would naturally occur in the passive mode (see Section 6.5).

Surface infiltration is difficult to accurately quantify since it is a transient event that depends on a number of complex factors including intensity-duration-frequency of precipitation, winter conditions, and unsaturated ground water flow. At present, best estimates are obtained by water budget analyses.

6.4.2 Methodology

Three types of water budget analyses were considered. The first, "Regional Streamflow Water Budget", is extracted from M.M. Dillon's surface water report for the Preferred Site (M.M. Dillon, 1987). It is based on regional streamflow data, with comparison to published regional water budget analyses.

The second type, the "Thornthwaite Water Budget", was undertaken by GLL using the method of Thornthwaite and Mather (1957). The assumptions used for this analysis are indicated in Figure 6-2.

The third type, the "Help Water Budget", was also undertaken by GLL using the "HELP" computer model developed by US EPA (Schroeder et al., 1983; details regarding the "HELP" model are presented in GLL, 1987a). The HELP model differs from the Thornthwaite method in that it performs water budget calculations on a daily rather than monthly basis, and it calculates infiltration based on both hydrologic and hydrogeologic conditions. The assumptions used in the HELP modelling are summarized in Figure 6-3.

Three types of precipitation data are used in the various water budgets in order to provide a range for annual leachate quantities:

- long-term average precipitation
- precipitation for an actual "average" or "typical" year (1961) as determined by Atmospheric Environment Service, Environment Canada
- precipitation for the wettest year available from record (1985)

The Welland meteorologic station records were used in all cases.

6.4.3 Results

Figure 6-4 summarizes the results of each of the water budget analyses. The components of the water budget shown in Figure 6-4 have been defined as follows.

FIGURE 6-2 ASSUMPTIONS USED IN THORNTHWAITE WATER BUDGET ANALYSIS

METHOD: Thornthwaite and Mather, 1957
(non-linear loss of soil moisture)

METEOROLOGICAL STATION: Welland, Ontario

TEMPERATURE DATA: Mean monthly long-term temperature data, Welland

PRECIPITATION DATA:
a. actual monthly precipitation for a typical "average" year (1961), Welland

b. actual monthly precipitation for the wettest year on record (1985), Welland

SOIL MOISTURE STORAGE: 50 mm

FIGURE 6-3 ASSUMPTIONS USED IN "HELP" MODELLING

METHOD: Hydrologic Evaluation of Landfill Performance, Schroeder et al., 1983

CLIMATOLOGIC DATA:

- actual daily precipitation for actual "average" year (1961), Welland station, repeated for 5 years
- actual daily precipitation for wettest year on record (1985), Welland station, repeated for 5 years
- mean monthly long-term temperature data, Welland station
- mean monthly long term solar radiation data, Welland station
- evaporative zone depth = 305 mm
- winter cover factor = 1.0
- leaf area indicies:

Days Since Jan.1	LAI
1	.00
31	.10
66	.20
99	.60
130	1.00
160	1.40
190	1.70
222	1.60
255	1.20
280	.80
310	.30
340	.10
366	.00

DESIGN DATA:

- SCS runoff curve number = 85 (low sensitivity)

SOIL DATA:

- Topsoil (vertical percolation)
  Thickness = 305 mm
  Evaporation Coefficient = 5.0 mm/day**0.5
  (low sensitivity)
  Porosity = 0.50
  Field Capacity = 0.35
  Wilting Point = 0.15
  Hydraulic Conductivity = 2E-6 m/s

- Recompacted Silt and Clay Cover (barrier)
  Thickness = 4700 mm
  Porosity = 0.50
  Field Capacitry = 0.45
  Hydraulic Conductivity = 1E-8 and 5E-8 m/s (sensitive)

Precipitation is the total moisture reaching the land surface from all sources including rain and snow. Evapotranspiration is moisture that returns to the atmosphere by the combined processes of evaporation and plant transpiration. Surplus water is the remainder of the precipitation after evapotranspiration is subtracted. The surplus water can be further partitioned into two components: runoff and infiltration. Runoff is water that moves off-site in the local surface drainage network while infiltration is the remainder of the surplus water that moves into the ground water system. All values shown in Figure 6-4 are per square metre of landfill surface area. The following discusses the results of the three types of water budgets individually.

Regional Streamflow Water Budget

The average annual long-term precipitation for the Welland station was partitioned into mean total surplus of 312 mm/a based on a regional discharge from the Welland River basin (M.M. Dillon 1987) with the remainder being evapotranspiration. The surplus was subsequently partitioned into 112 mm/a of infiltration that results in baseflow (on the basis of a regional baseflow to surplus ratio of 0.36 as reported in Moin and Shaw, 1985), and the remaining 200 mm/a as overland runoff. This suggests that infiltration through the landfill cover, and thus the quantity of leachate generation, should not exceed the regional infiltration through the landfill cover, and thus the quantity of leachate generation, should not exceed the regional infiltration value.

Thornthwaite Water Budget

Water budget analyses using the method of Thornthwaite and Mather (1957) were performed for both a typical "average" year of precipitation (1961) as well as the wettest year available on record (1985) in order to provide a range. The results are shown in Table 6-4. Precipitation is partitioned into evapotranspiration and surplus water by direct calculation. However, partitioning the surplus water into runoff and infiltration in a manner that accounts for the presence of a landfill and an actively operating underdrain is difficult. In this case, runoff was conservatively assumed to be limited to the calculated snowmelt runoff, with the remainder being infiltration.

FIGURE 6-4 SUMMARY OF WATER BUDGET ANALYSES FOR THE PREFERRED SITE

	M.M.DILLON 1987 REGIONAL LONG-TERM AVERAGE	GLL THORNTHWAITE AVERAGE YEAR (1961)	GLL THORNTHWAITE WETTEST YEAR (1985)	GLL HELP AVERAGE YEAR (1961)	GLL * HELP AVERAGE YEAR (1961)	GLL HELP WETTEST YEAR (1985)
PRECIPITATION	938	933	1203	934	934	1204
EVAPOTRANSPIRATION	626	544	517	460	468	464
SURPLUS WATER	312	389	686	474	466	740
RUNOFF	200	**223	**333	166	298	340
INFILTRATION	***112	166	353	308	167	400

NOTES: All values in mm/a per square metre of landfill area

* Hydraulic conductivity of clay cover 1E-8 m/s
** Snow melt runoff, assumed to be conservative minimum runoff
*** Baseflow, calculated from regional baseflow : surplus ratio of 0.36 (Moin and Shaw, 1985).

"HELP" Water Budget

The "HELP" model predicts each component of the water budget shown in Figure 6-4 by direct daily calculation. Some sensitivity testing was performed with the model for input parameters that were considered to be estimates. Two of these parameters, SCS runoff curve number and coefficient of evaporation, were determined to be insensitive over a reasonable range, however, the results were very sensitive to the hydraulic conductivity of the silt and clay cover, as might be expected. As shown in Figure 6-4, reduction in hydraulic conductivity of a half order of magnitude dramatically reduces the predicted infiltration.

6.4.4 Discussion

The regional long-term average water budget appears to have significant limitations when applied on a site-specific basis. For instance, it assumes that all precipitation not reaching the Welland River by either surface runoff or base flow is evapotranspirated. This approach neglects the fact that recharge to the regional bedrock aquifer(s) occurs throughout the Welland River drainage basin (GLL 1987b). This recharge is incorrectly included in the evapotranspiration component, thus the actual evapotranspiration may be somewhat lower than predicted and the surplus water somewhat greater.

In addition, the baseflow ratio presented by Moin and Shaw (1985) is regional in nature, and includes a variety of hydrogeologic settings. Utilizing this ratio to partition runoff and infiltration at the Preferred Site over an actively operated landfill may not be appropriate.

The Thornthwaite water budget results in lower values of evapotranspiration and greater values of surplus water than the regional analysis (Figure 6-4). These may be somewhat more reasonable on a site-specific basis given the previous discussion regarding the partitioning problems with the regional analysis. However, the Thornthwaite method also suffers in that it cannot reasonably partition runoff and infiltration over an actively operating landfill. In Figure 6-4, the calculated snowmelt runoff has been assumed to equal the total runoff, with the remainder of the surplus

occurring as infiltration. Snowmelt is considered to be a conservative estimate of minimum total runoff.

The "HELP" model calculated even lower evapotranspiration quantities and greater surplus water quantities than the Thornthwaite method (Figure 6-4). It actually calculates the partitioning between infiltration and runoff; however, these were found to be sensitive to the hydraulic conductivity of the silt and clay cover. Specifying a hydraulic conductivity of 1×10^{-8} m/s, the resulting infiltration is similar to that predicted by the Thornthwaite method.

Inflow to the active underdrains from the underlying native silt and clay soils will be negligible relative to the infiltration at the landfill surface (likely less than 1%). Also, the values presented here reflect annual totals. Other factors such as intensity-duration-frequency may have to be considered. The "HELP" model can provide daily accounting of the water budget; this level of detail may be appropriate at the detailed design phase.

It would be useful to compare the predictions made in this study to actual field data. Unfortunately, there is a general paucity of published data regarding the performance of clay covers over actively operating underdrains in landfills.

6.4.5 Recommendations

The following recommendations result from this study:

1) The results of the water budget analyses presented previously represent our best possible estimates of leachate generation at this time.

2) To be very conservative, the values of "surplus water" should be used as estimates of potential infiltration and leachate generation in further facilities development. The "HELP" model predicts the greatest (most conservative) leachate quantities of 474 mm/a (per square metre of landfill area) for an average year to 740 mm/a for the wettest year on record.

3) If a less conservative approach can be justified, then the values of "infiltration" should be used as estimates of potential leachate generation. The results of the "HELP" modelling are again the most conservative ranging from 308 mm/a for an average year to 400 mm/a for the wettest year on record, given current assumptions regarding cover permeability.

4) Consideration of intensity-frequency-duration and other more detailed analyses may be warranted, depending on the nature of the design problem.

5) Previous studies have indicated that the hydraulic conductivity of the silt and clay cover is not a critical factor in the passive mode (see Section 3.3.2). However, the "HELP" modelling demonstrates that lower hydraulic conductivities are very important in minimizing leachate generation in the active mode. For example, a reduction of cover hydraulic conductivity by half an order of magnitude (which should be attainable with good compaction techniques alone) results in a 46% decrease in leachate quantities based on the HELP modelling results. Therefore, one or more of the following strategies may be considered:

   a) maximum possible cover compaction,
   b) inclusion of a synthetic membrane barrier in the cover,
   c) periodic testing of cover permeability after construction to monitor changes due to weathering, and
   d) monitoring of cover infiltration rates.

   It is important to note that the cover will be accessible, therefore improvements such as recompaction or the addition of a synthetic membrane to reduce infiltration can be made at any time. Since the active mode is a contingency only, cover improvement may be made as necessary if and when the contingency is required. This is further discussed in Section 6.5.4.

6) Contacts with selected landfill operators may provide field data regarding infiltration through clay covers overlying actively operated underdrains; such information may be useful at the detailed design phase.

6.5 LANDFILL UNDERDRAIN

6.5.1 Introduction

OWMC's shallow entombed landfill will contain an underdrain layer, although the landfill is designed to be operated in the passive mode (M.M. Dillon 1986). Therefore, the underdrain system is expected to be used only if monitoring indicates that contaminants are moving away from the base of the landfill into the deep ground water flow system at a significantly faster rate or at greater concentrations that were predicted.

M.M. Dillon Ltd. identified three potential underdrain design alternatives:

Alternative 1: drainage layer, multiple sumps;

Alternative 2: drainage layer, perimeter drain pipes multiple wet wells; and

Alternative 3: drainage layer, underdrain pipe network, multiple wet wells.

These three design alternatives are illustrated in a very schematic fashion in Figures 6-5 to 6-7.

M.M. Dillon Ltd. is undertaking a comparative evaluation of the three alternative underdrain systems described above. One of the criteria in the evaluation is performance. This section discusses the hydrogeologic performance of each alternative and provides the necessary input to the comparative evaluation.

A range of hydrogeologic performance is possible for each of the design alternatives depending on hydraulic parameters such as drain or sump spacing or the rate of

FIGURE 6-5: SCHEMATIC ILLUSTRATION OF SUMP SYSTEM (ALTERNATIVE 1)

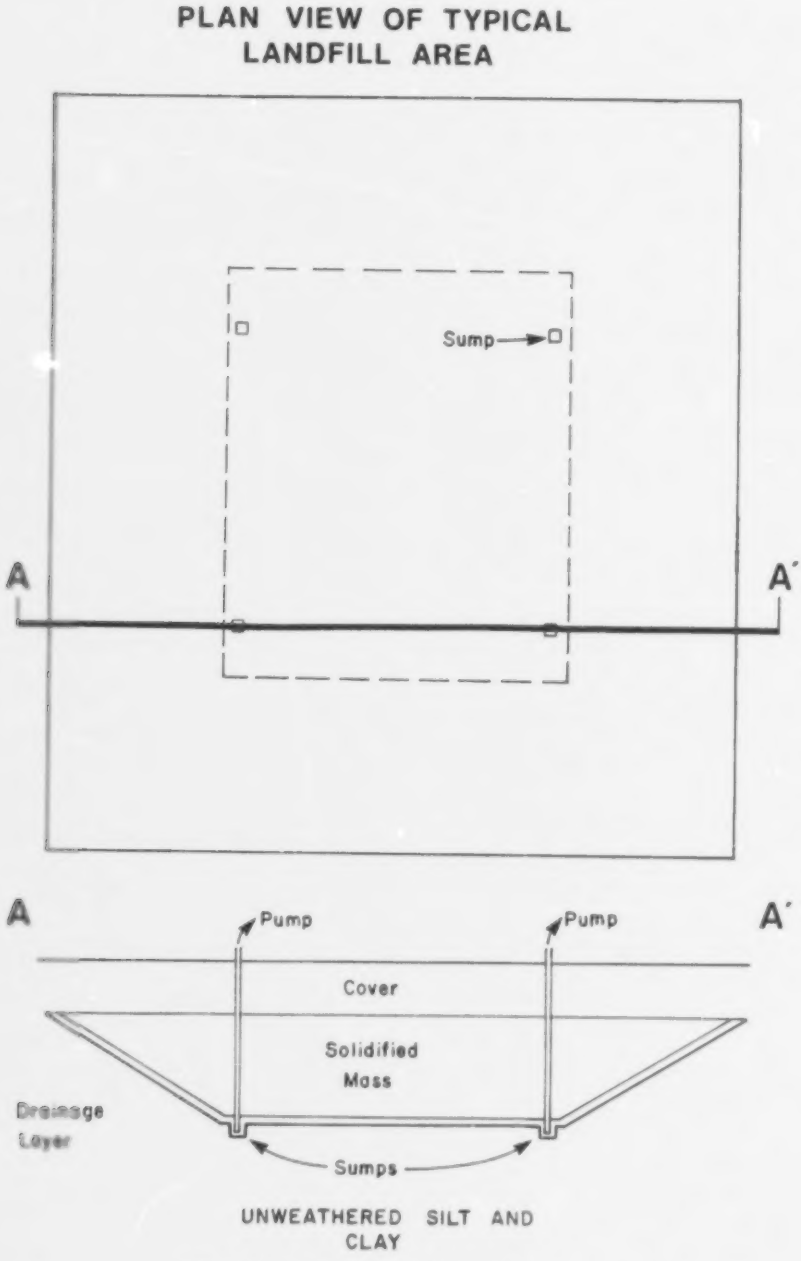


FIGURE 6-6: SCHEMATIC ILLUSTRATION OF PERIMETER DRAIN PIPES (ALTERNATIVE 2)

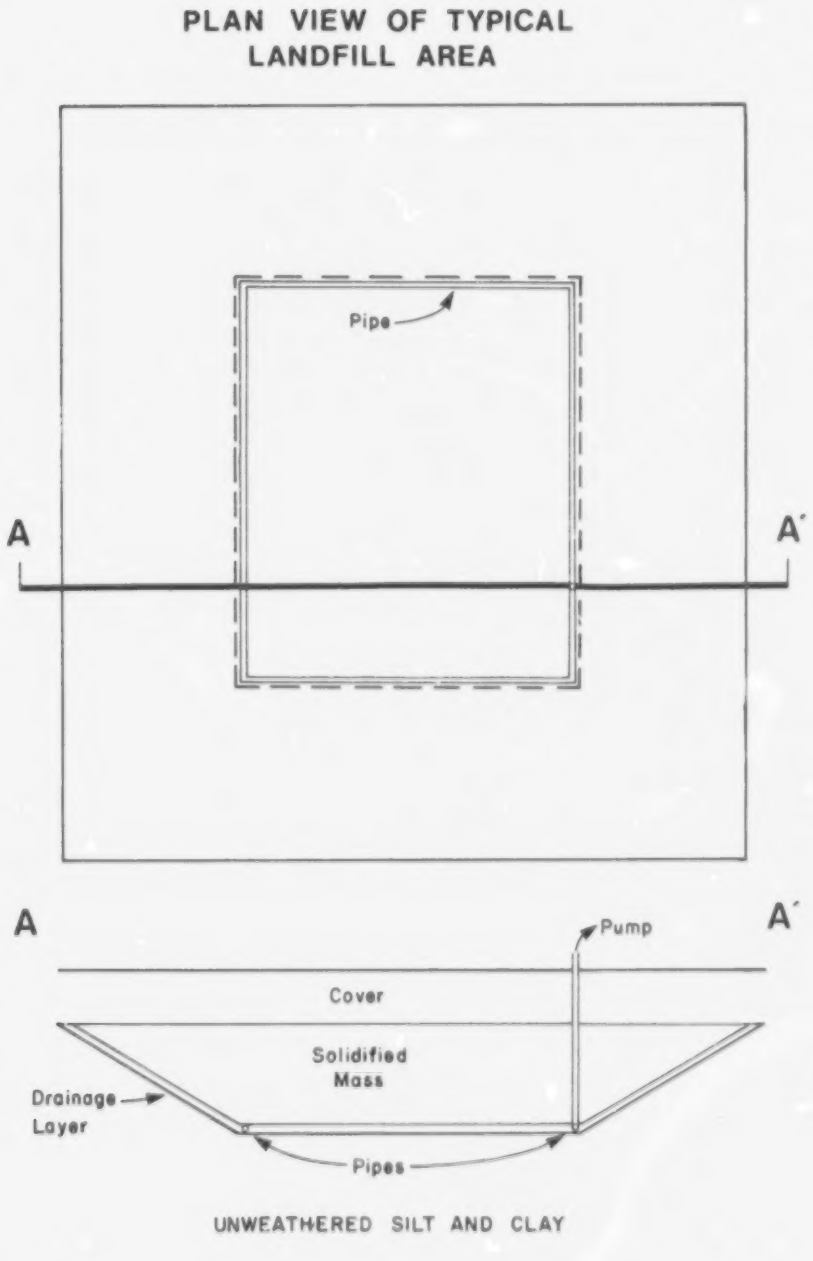
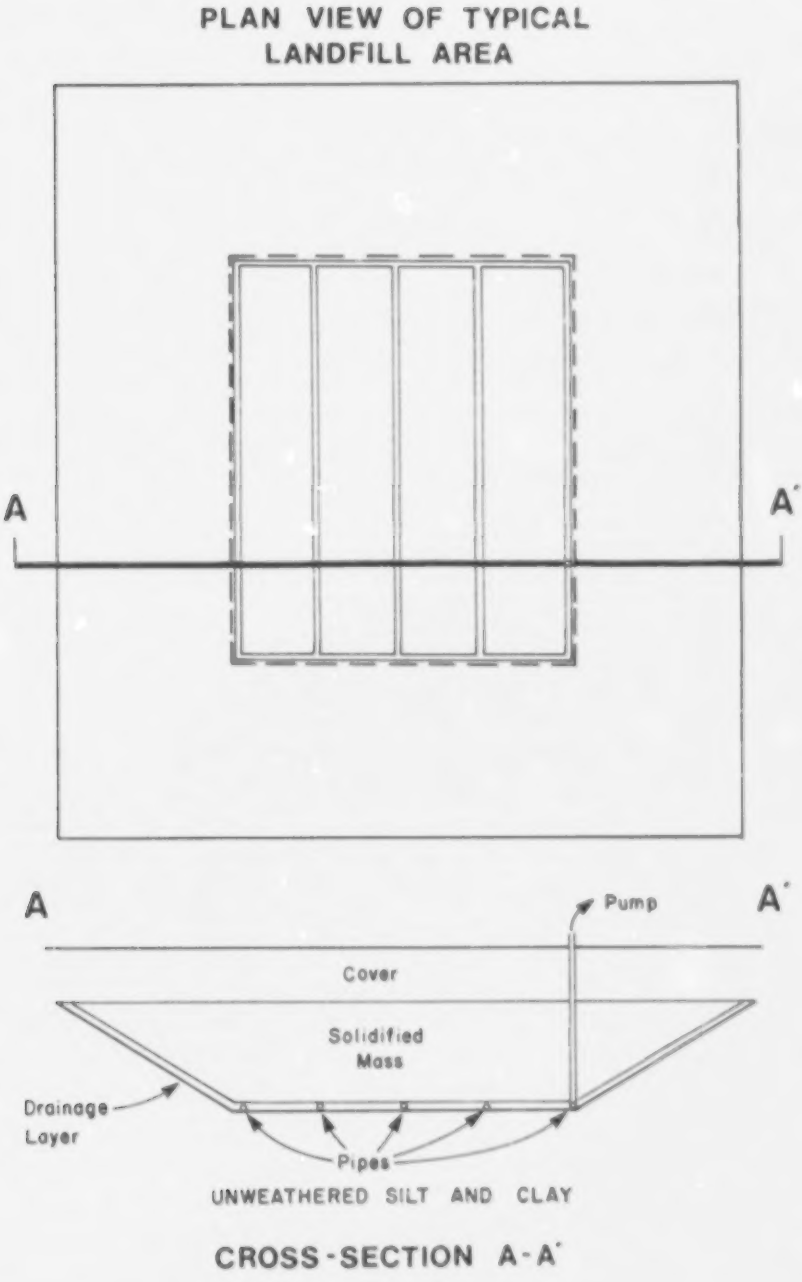


FIGURE 6-7: SCHEMATIC ILLUSTRATION OF UNDERDRAIN PIPE NETWORK (ALTERNATIVE 3)



pumping. It was determined that Gartner Lee Limited would provide a preliminary assessment of the required hydraulic design that would allow each of the alternative underdrain designs to achieve a minimum performance standard (which is discussed in the following sections). In this way, the resulting designs would be considered to have equal performance, and the selection of one of the alternatives would be made on the basis of engineering criteria to be assessed by M.M. Dillon.

The analyses discussed above were completed using a set of assumptions regarding the material properties and configuration of the landfill. Although the assumptions are consistent with previous design work (GLL 1987a; M.M. Dillon 1986), a second objective of the study was to examine the sensitivity of the underdrain design to a possible range of values for certain key parameters including:

- solidified mass hydraulic conductivity,
- drainage layer hydraulic conductivity,
- drainage layer thickness, and
- cover infiltration rate.

6.5.2 Methodology

The performance analysis of the alternative underdrain designs is a complex hydrogeologic problem. Therefore, ground water flow modelling was used in this study. Two numerical computer models, named "FLONET" and "AQUIFER", were used along with a number of analytical solutions.

The "FLONET" model is documented fully in Appendix I of the GLL (1987) report entitled "Site Assessment Phase 4B: Geology, Hydrogeology and Geotechnics, Baseline Conditions". The "AQUIFER" model is a quasi-three-dimensional finite element model developed by the University of Waterloo (Frind, 1972). Further details regarding the "AQUIFER" model are contained in Appendix A of this report.

The following briefly describes the steps undertaken in this assessment and the rationale for the use of the various models:

Step 1: Minimum Performance Standard

A minimum performance standard was established that describes a basic acceptable level of performance that each alternative must achieve.

Step 2: Base Case Assumptions

The "base case" assumptions for material properties, landfill configuration, and hydraulic parameters were established.

Step 3: Base Case Drain Pipe Spacing

The "FLONET" model was used to determine the base case drain pipe spacing required to maintain the minimum performance standard under long-term steady state flow conditions. This analysis is applicable to both Alternative 2 and Alternative 3 since perimeter drains are merely a specific case of an underdrain pipe network (i.e., pipes spaced at a constant distance equal to the landfill area width).

Step 4: Model Calibration

The "FLONET" model is more accurate than the "AQUIFER" model for assessing underdrain performance for the OWMC landfill conditions since it calculates the final position and shape of the steady state water table that results in the landfill. However, "FLONET" is strictly a two-dimensional model and as such cannot be used to assess the performance of sumps (Alternative 1), which are a three-dimensional flow problem. Therefore, "AQUIFER" was used to analyze sump performance. First, however, "AQUIFER" was used to re-evaluate the drain pipe problem described in Step 3. The position of the water table (which must be fixed and flat with "AQUIFER") was adjusted until the resulting hydraulic head distribution in the drainage layer was reasonably close to that determined using "FLONET".

Step 5: Base Case Sump Spacing

The "AQUIFER" model was used to determine the base case sump spacing required to maintain the minimum performance standard under long-term steady state conditions. The water table position used was that determined by calibration of the "FLONET" and "AQUIFER" models described in Step 4 above.

Step 6: Sensitivity Study

The "FLONET" model was used to examine the sensitivity of the long-term steady state drain spacing to the following range of key design parameters:

- cover infiltration rate: 0.10 to 0.70 m/year
- drain pipe hydraulic head: 0.3 to 2.0 m
- solidified mass hydraulic conductivity: 5×10^{-9} to 5×10^{-7} m/s
- drain layer thickness: 0.1 to 1.0 m, and
- drain layer hydraulic conductivity: 1×10^{-5} to 1×10^{-3} m/s.

The sensitivity analyses were conducted by varying one parameter at a time within the indicated range, but otherwise using base case assumptions.

Step 7: Short-Term Pumping Capacities

Initially, pumping rates greater than the average long-term infiltration rate will likely be required in order to remove sufficient leachate from storage in the solidified mass, lower the water table in the landfill, and thereby allow the minimum performance standard to be met at steady state. The "AQUIFER" model was used to analyze this short-term response and establish maximum short-term pumping capacities. This was accomplished by specifying an initial water table level of 1 m below ground surface, then simulating the transient response to a variety of pumping rates. The required maximum short-term pumping rate was the one which caused the system to reach the steady state conditions modelled in Steps 3 and 5. Base case conditions and the appropriate drain pipe or sump spacing determined in Steps 3 and 5 were used.

Step 8: Transient Response Time

There will be a period of time in which the pumping rate can be reduced from its high initial level described in Step 7 to the long-term average infiltration rate once steady state conditions are achieved in the landfill.

None of our present ground water flow models predict the decay of pumping rate with time; this can most effectively be accomplished in the field by monitoring underdrain performance. However, the analytical solution presented by Cedergren (1967, pp. 133-19) can be used to roughly estimate the overall time required for the solidified mass to desaturate and reach steady state conditions. Furthermore, the time required for an instantaneous change in hydraulic head (turning on the underdrain pumps, for example) to propagate through the solidified mass was approximated using the technique outlined by Wolff (1970). This provides an estimate of the lag time for response from the solidified mass.

6.5.3 Results

Step 1: Minimum Performance Standard

The minimum performance standard for each of the three alternative underdrain designs was defined as the capability to create and maintain a hydraulic head throughout the drainage layer that would be equal to or less than the hydraulic head in the underlying bedrock aquifer. The effect of this is to produce a net zero or upward gradient from the aquifer towards the base of the landfill and thus prevent the outflow of leachate. This is illustrated in Figure 6-8 relative to the (arbitrarily) selected datum at the base of the landfill excavation.

It is important to recognize that contaminant species may still be transported downwards at extremely slow rates under zero or upward flow conditions by the process of diffusion.

Step 2: Base Case Assumptions

Figure 6-8 also illustrates most of the base case assumptions used in the analyses. The assumptions are consistent with those made during earlier design work.

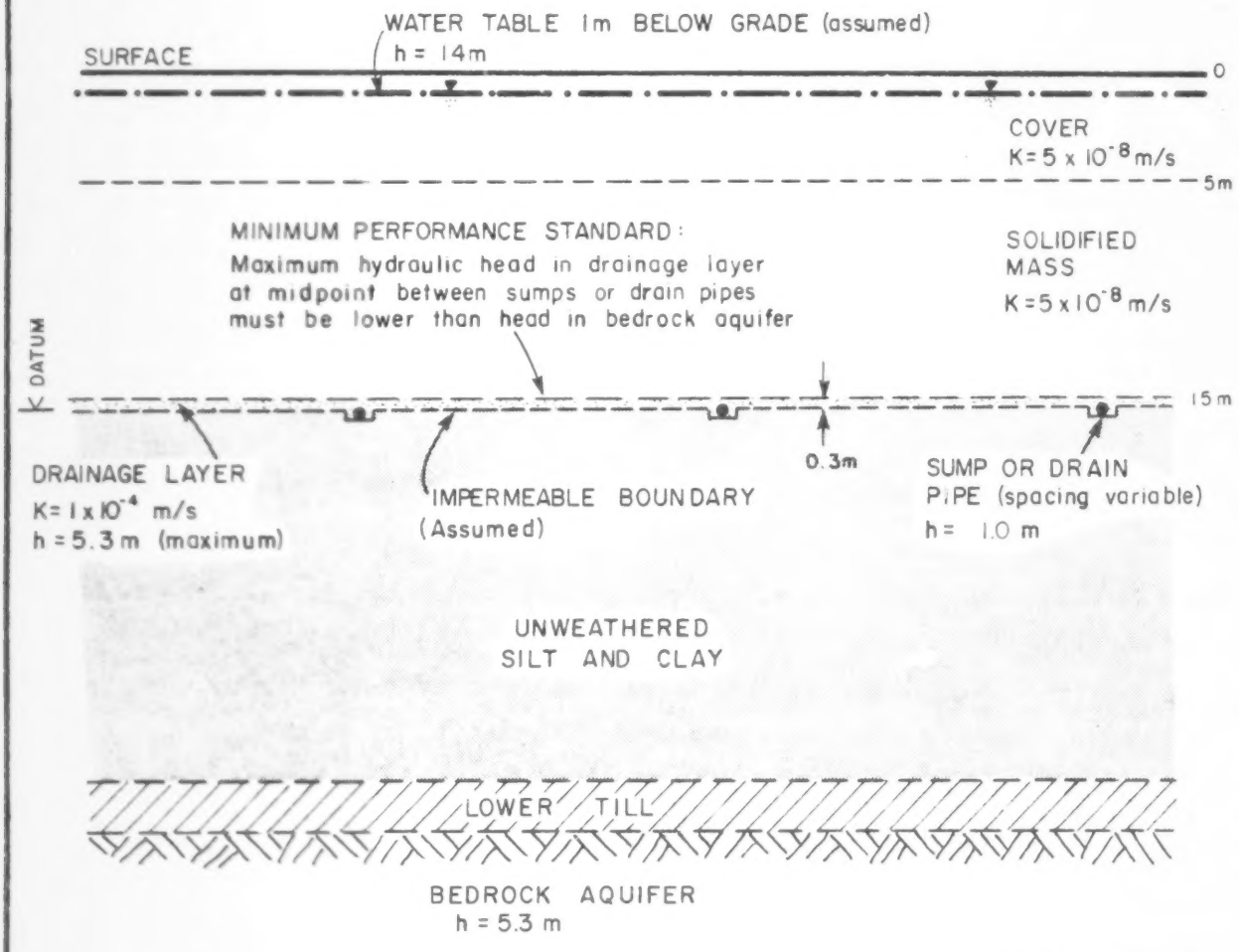


Figure 6-8

MINIMUM PERFORMANCE STANDARD AND MODELLING ASSUMPTIONS

Gartner Lee Limited

The average long-term infiltration rate for active landfill operation (which equals the average pumping rate at steady state since there is negligible inflow to the drainage layer from the underlying unweathered silt and clay) is assumed to be 0.3 m/year per square metre of landfill area. This value was obtained from our earlier work regarding estimated leachate quantities for active landfill operations (described in Section 6.4).

Step 3: Base Case Drain Pipe Spacing

An infinite number of steady state solutions are possible that will achieve the minimum performance standard, depending on the hydraulic head maintained in the drain pipes (which can be adjusted by short-term increases in the pumping rate). A low drain pipe head is desirable in order to maintain maximum gradients in the drain layer. However, the drain layer should not be desaturated since this can potentially cause chemical precipitation in the drains which could lead to clogging as well as causing the pumps to break suction. Therefore, a drain pipe head of 1 m above datum was assumed for base case calculations. Other head values were examined as part of the sensitivity study in Step 6.

It should be noted that if the head in the drain layer is about 1 m above datum, the drainage layer up the side slopes of the landfill will likely be dewatered to some extent, although this was not explicitly modelled in this study.

"FLONET" predicted that the maximum steady state head in the underdrain layer for base case assumptions and a drain spacing of 300 m would be about 4.8 m. This is less than the minimum performance standard of 5.3 m (the head in the bedrock aquifer). Therefore, perimeter drains, whose maximum spacing should not exceed about 300 m, would appear to be adequate at these steady state conditions. Of course, an underdrain pipe network with closer spacings will also suffice. If an underdrain pipe network is used, the maximum distance to the nearest edge of the landfill, where no other pipes are present, should not exceed about 150 m.

Step 4: Model Calibration

The base case, steady state "FLONET" analysis described in Step 3 above was repeated using the "AQUIFER" model. The position of the water table was adjusted until the

steady state hydraulic head distribution in the underdrain layer was similar between the two models. The calibration was reasonably good when "AQUIFER" was given a water table level of about 5 m above the base of the landfill, as indicated by the following results:

	"FLONET"	"AQUIFER"
Hydraulic Head in Drain Pipe (m)	2.0	2.6
Maximum Hydraulic Head in Drain Layer (m) (at midpoint between drains)	5.8	5.0

The differences between the model results cannot be exactly resolved because "FLONET" produces a realistic water table that is lower above the drain pipes and has a mound between drain pipes, a shape that would result from infiltration that was evenly distributed over the entire water table surface. "AQUIFER", on the other hand, can only allow for a flat water table, and while the total recharge equals that of "FLONET", it is greater over the drain pipes and less at the midpoint between them. However, since "AQUIFER" must be used to assess sump performance, assuming a flat water table at 5 m above datum appears to be a reasonable approximately based upon the calibration presented here.

Step 5: Base Case Sump Spacing

"AQUIFER" was used along with the base case assumptions and the water table of 5 m above datum determined in Step 4 to assess the steady state sump spacing that would be required to maintain the minimum performance standard. The results indicate that steady state conditions similar to those determined for the drain pipe analysis (i.e., minimum head at the sump of 1 m above datum and maximum head in the underdrain layer of 5.3 m or less) were reached for sump spacings in the order of 140 m. The maximum distance from a sump to the nearest edge of the landfill, where no other sumps intervene, should not exceed about 70 m.

Step 6: Sensitivity Study

The "FLONET" model and the steady state drain pipe spacing analysis described in Step 3 were used as the basis for the sensitivity study. The sensitivity study of the sump alternative was not specifically examined, although the drain pipe sensitivities will generally apply.

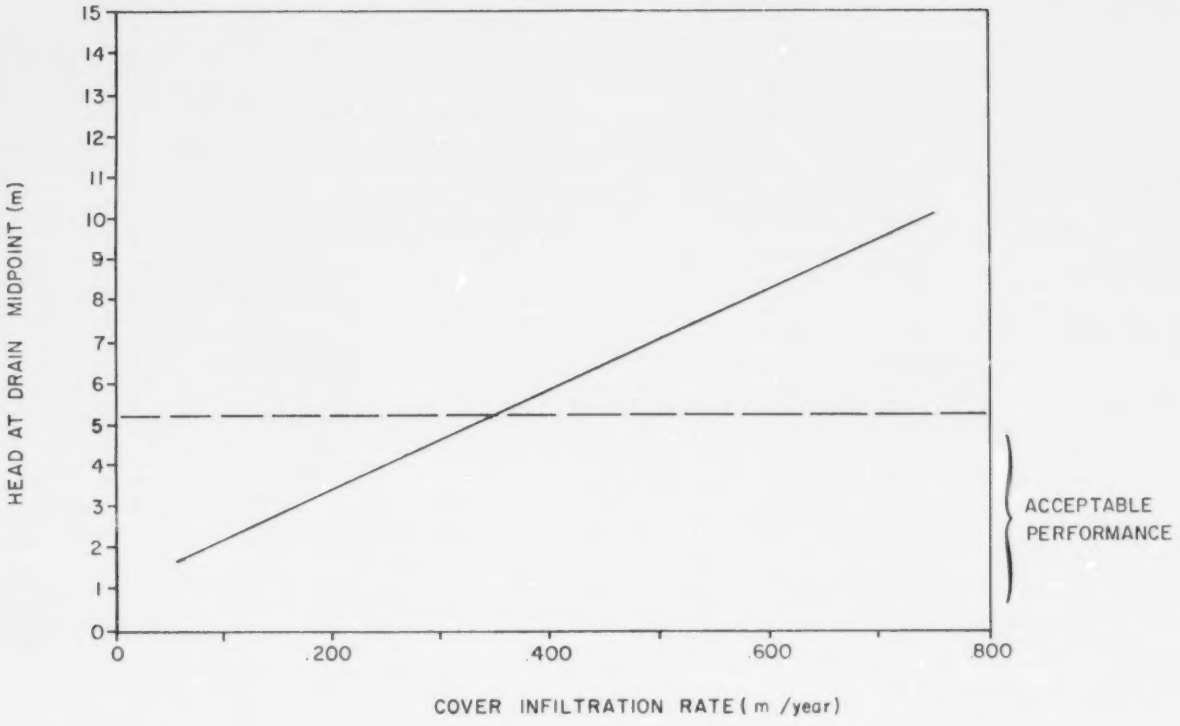
Figure 6-9 through 6-13 illustrate the results of the sensitivity analyses for the following parameters, respectively:

- cover infiltration rate: 0.10 to 0.70 m/year
- drain pipe hydraulic head: 0.3 to 2.0 m
- solidified mass hydraulic conductivity: 5×10^{-9} to 5×10^{-7} m/s
- drain layer thickness: 0.1 to 1.0 m, and
- drain layer hydraulic conductivity: 1×10^{-5} to 1×10^{-3} m/s.

Each of the figures shows the sensitivity with respect to the maximum hydraulic head at the midpoint between the drain pipes. The range of values for which the performance is acceptable is indicated as those results where the maximum head in the underdrain layer is less than the minimum performance standard of 5.3 m.

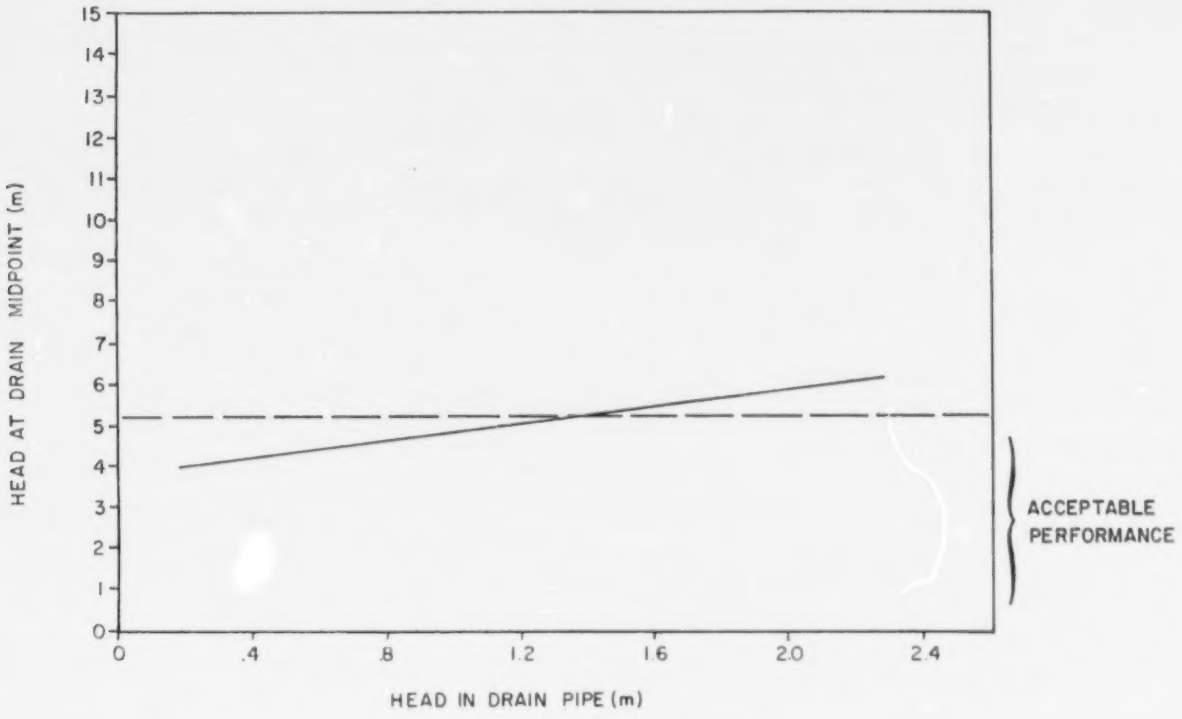
Over the ranges studied, the drain pipe performance was found to be relatively insensitive to the hydraulic conductivity of the overlying solidified mass, moderately sensitive to the head maintained in the drain pipes and to the cover infiltration rate, and very sensitive to the drain layer thickness and the hydraulic conductivity of the underdrain layer material. If the underdrain material were one order of magnitude lower in hydraulic conductivity than the base case assumption, which might occur as a

FIGURE 6-9 SENSITIVITY TO COVER INFILTRATION RATE



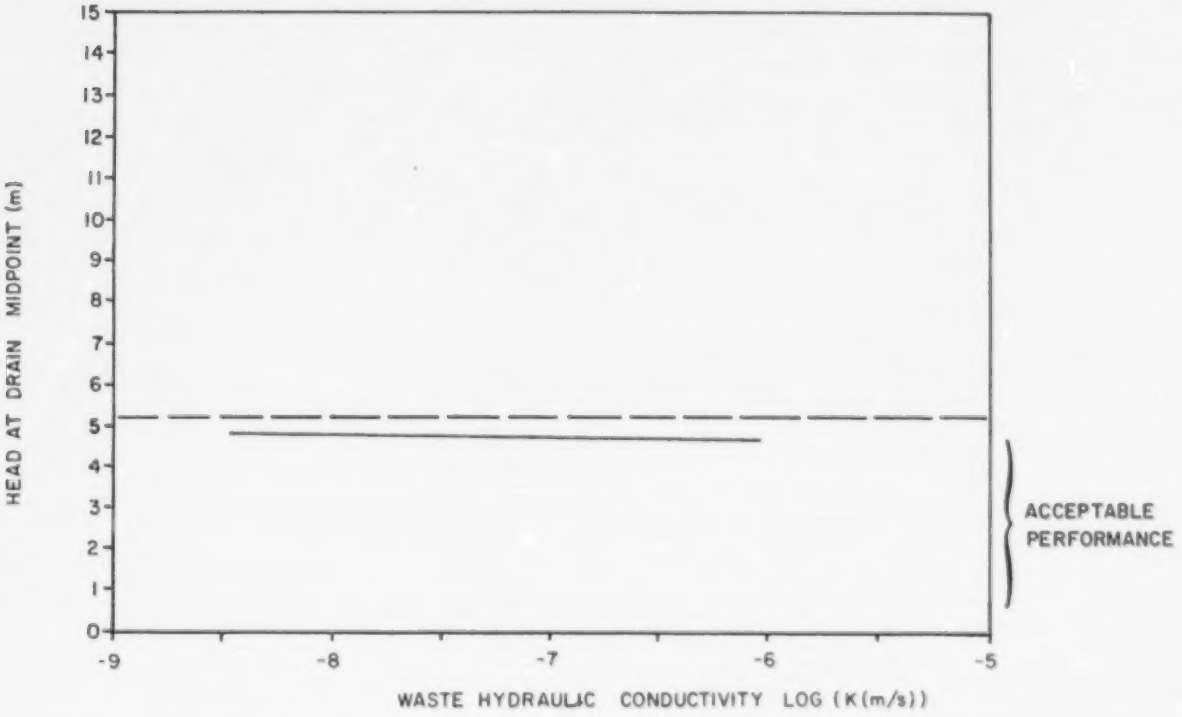
Perimeter Drains
Spacing = 300 m
K Drain Layer = 1×10^{-4} m/s
K Cover/Waste = 5×10^{-8} m/s
Drain Layer Thickness = 0.3 m
Drain Head = 1.0 m

FIGURE 6-10 SENSITIVITY TO DRAIN PIPE HEAD



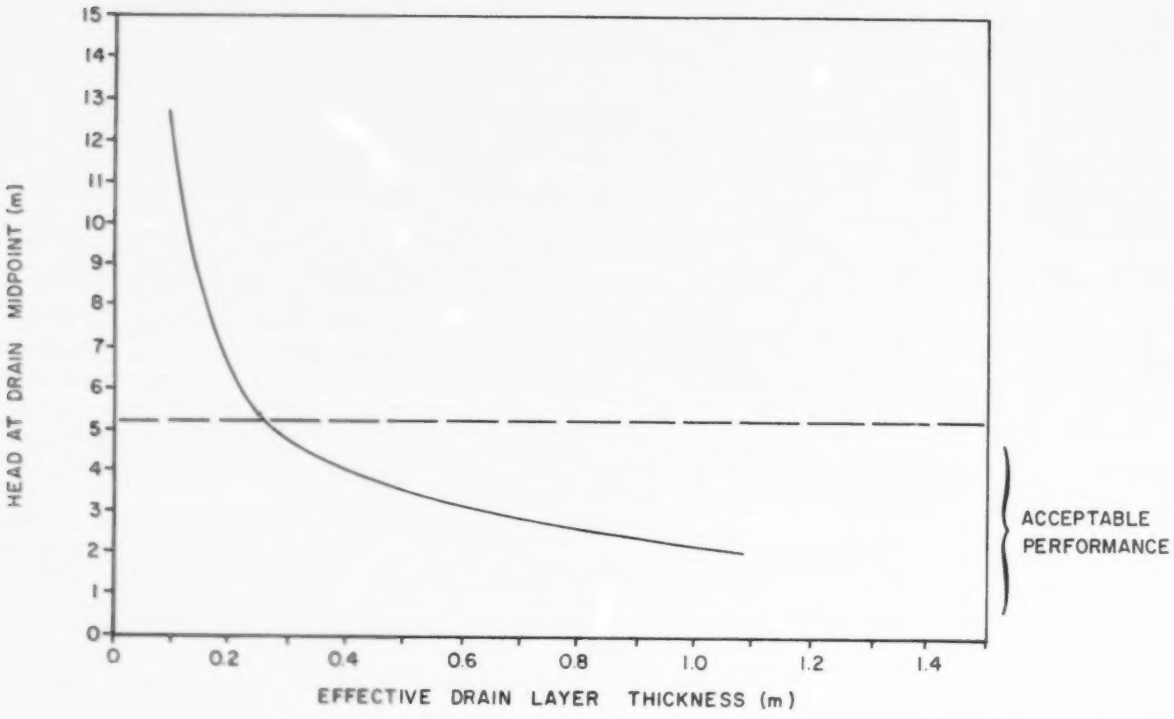
Perimeter Drains
Spacing = 300 m
Infiltration = 308 mm/a
K Cover/Waste = 5×10^{-8} m/s
K Drain Layer = 1×10^{-4} m/s
Drain Layer Thickness = 0.3 m

FIGURE 6-11 SENSITIVITY TO WASTE HYDRAULIC CONDUCTIVITY



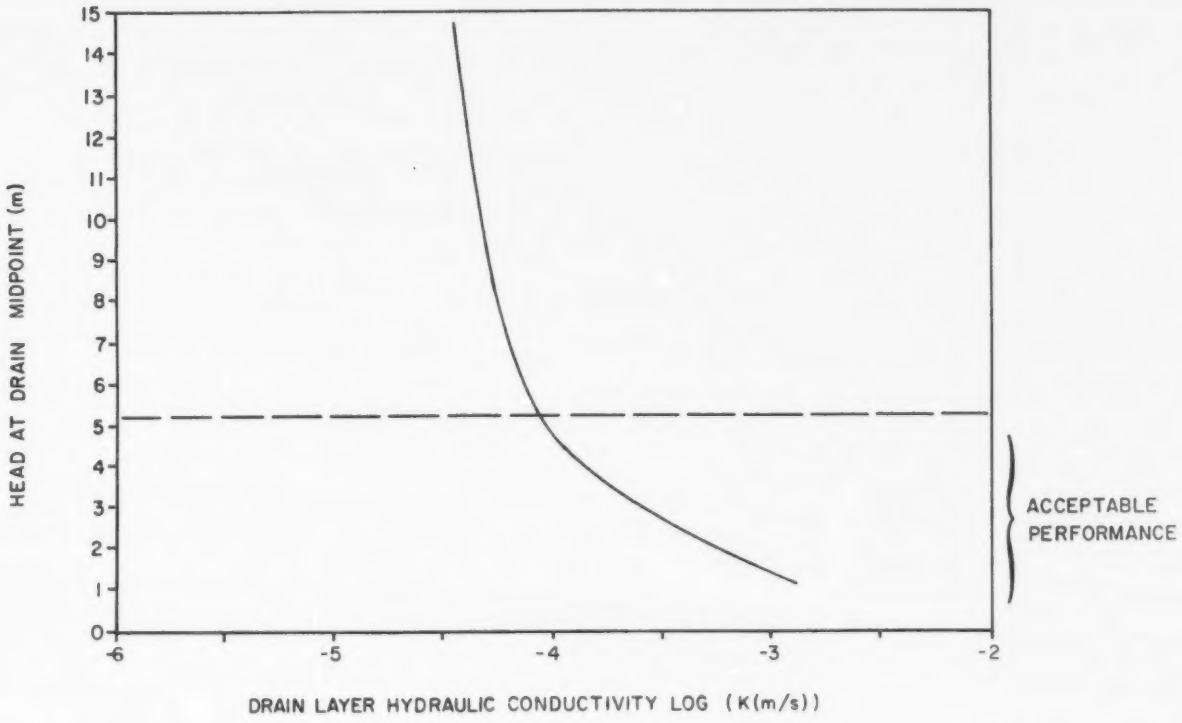
Perimeter Drains
Spacing = 300 m
Infiltration = 308 mm/a
K Drain Layer = 1×10^{-4} m/s
Drain Layer Thickness = 0.3 m
Drain Head = 1.0 m

FIGURE 6-12 SENSITIVITY TO DRAIN LAYER THICKNESS



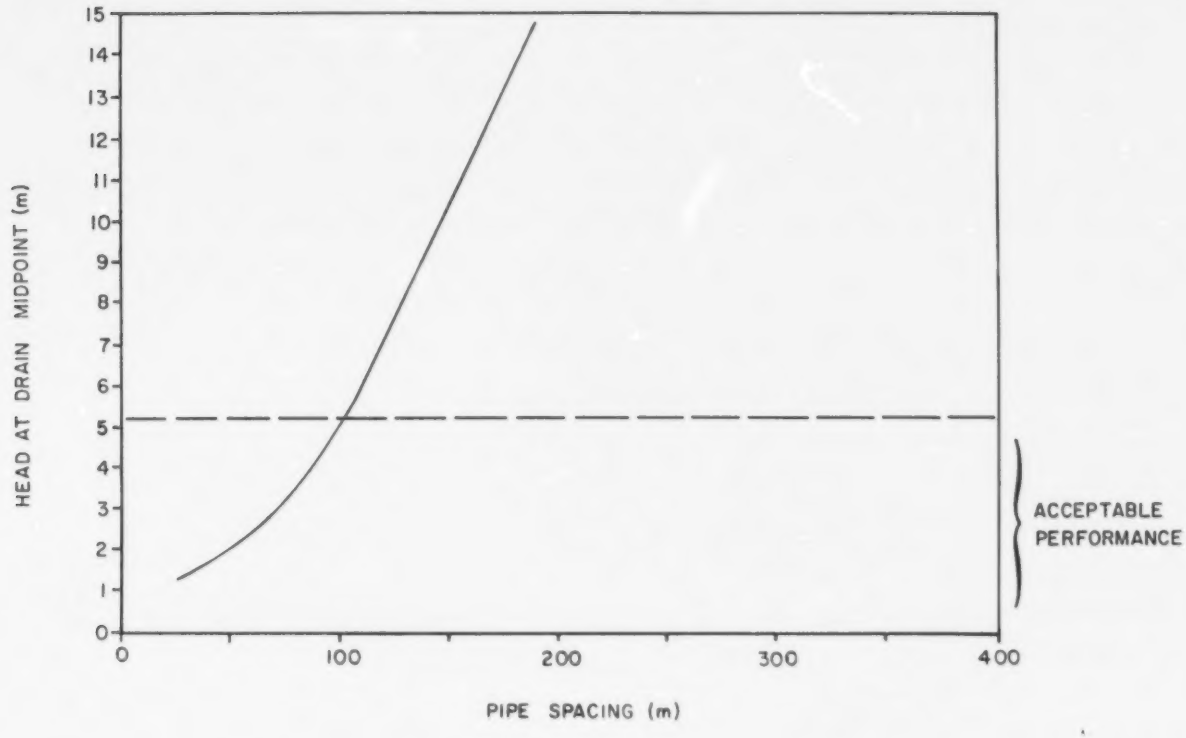
Perimeter Drains
Spacing = 300 m
Infiltration = 308 mm/a
K Cover Waste = 5×10^{-8} m/s
K Drain Layer = 1×10^{-4} m/s
Drain Head = 1.0 m

FIGURE 6-13 SENSITIVITY TO DRAIN LAYER HYDRAULIC CONDUCTIVITY



Perimeter Drains
Spacing = 300 m
Infiltration = 308 mm/a
K Cover/Waste = 5×10^{-8} m/s
Drain Layer Thickness = 0.3 m
Drain Head = 1.0m

FIGURE 6-14 SENSITIVITY TO DRAIN PIPE SPACING



Underdrain Network
Infiltration = 308 mm/a
K Drain Layer = 1×10^{-5} m/s
K Cover/Waste = 5×10^{-8} m/s
Drain Layer Thickness = 0.3 m
Drain Head = 1.0 m

result of clogging for instance, then Figure 6-14 shows that a drain pipe spacing of approximately 100 m or less would be necessary to offset this effect. At this point, perimeter drains would no longer be adequate. Considerations such as these must be made in establishing the factor of safety for the engineering design.

Step 7: Short-Term Pumping Capacities

The transient "AQUIFER" modelling indicated that an initial pumping rate equivalent to about 1.0 m/year of infiltration (in other words, a total quantity of about 1.0 m/year per square metre of landfill area) would be required to cause the desired steady state conditions to eventually be reached in the drainage layer for sumps. This is approximately three times the predicted long-term average pumping rate of 0.3 m/year required at steady state.

Similar modelling of the drain pipe alternatives gave an interesting result. Increasing the pumping rate in the drain pipes did not achieve the required head reduction throughout the drainage layer, even if the drain layer was desaturated around the drain pipe at pumping rates equivalent to 1.0 m/year or greater. This means that the drain pipe spacing is too wide to handle the leachate quantities produced when the drains are initially turned on and also meet the minimum performance standard. Further adjustments to the drain pipe spacing resulted in a required spacing of about 150 m and a pumping rate equivalent to about 1.2 m/year to meet both of these conditions. This seems to rule out the use of perimeter drains since they would be spaced at approximately 300 m.

Assessment of the transient response within the underdrain layer itself showed that for a reasonable range of storativity values of 1×10^{-5} to 1×10^{-4}, the minimum performance standard will be reached within days of turning on the pumping system at the higher initial pumping rates discussed above.

It is important to note that the above analyses were based on the premise that the minimum performance standard must be met as quickly as possible after turning on the pumps. However, some longer period may be acceptable given the slow nature of ground water flow and contaminant movement beneath the landfill. Therefore, a

wider range of performance options may be available. For example, if perimeter drains spaced at about 300 m were used and the pumps were started at an initial rate of 1.0 m/year (or perhaps slightly less depending on the tendency to desaturate around the pipes), then the desired steady state would eventually be reached, although not in the timeframe of several days discussed above. The range of performance options should be considered at the detailed design stage.

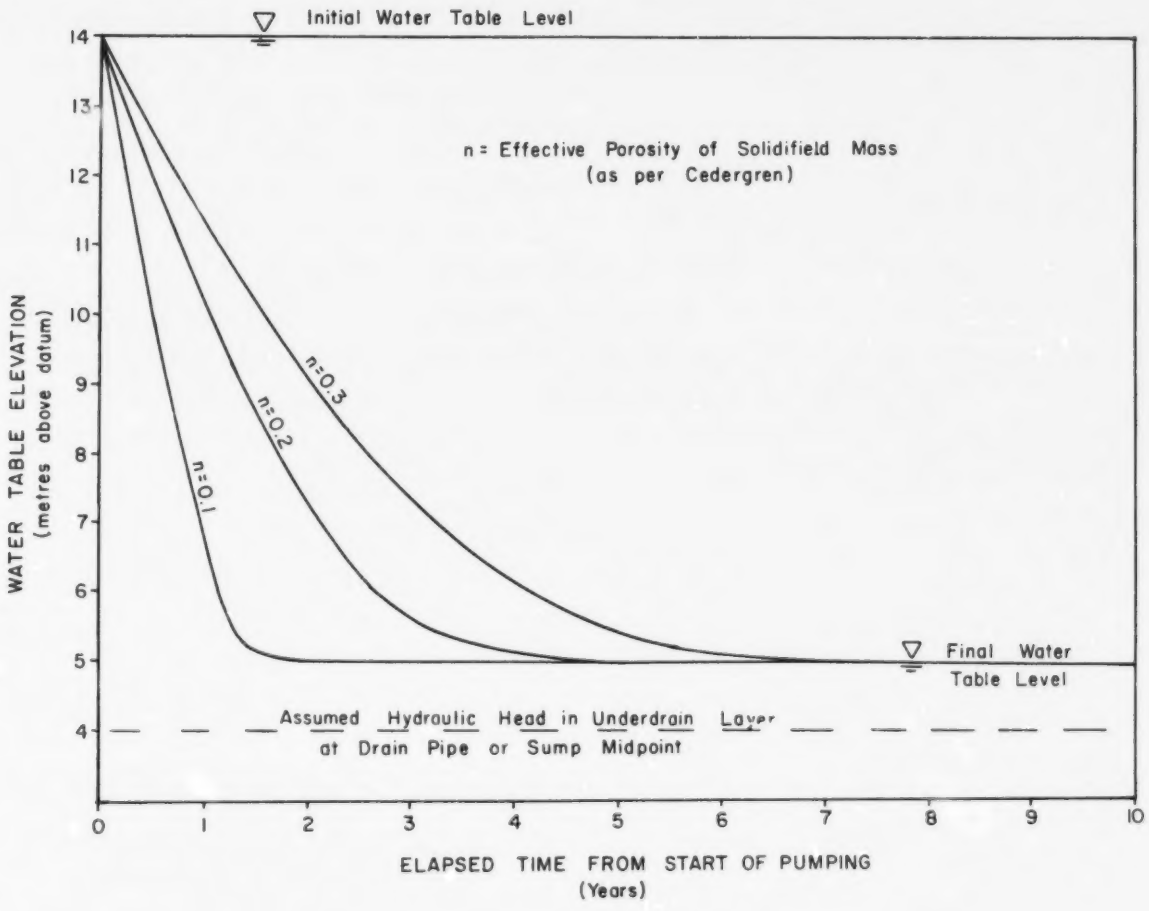
Step 8: Transient Response Time

The outstanding issue is the time period over which the pumping rate must exceed the long-term average infiltration rate in order to deplete the leachate storage within the landfill while maintaining the minimum performance standard in the underdrain layer. Neither "FLONET" nor "AQUIFER" can predict the transient time period along with the decrease of pumping rate with time. However, the time required to desaturate the solidified mass down to the final water table position can be estimated using the method outlined in Cedergren (1967). This is actually a one-dimensional flow calculation based on Darcy's Law. In this case, the cover infiltration of 0.3 m/year was added at each calculation step. Since the effective porosity (defined by Cedergren as total porosity minus unsaturated moisture retention) of the solidified mass is unknown, a range of values from 0.1 to 0.3 were tested.

Figure 6-15 shows the variance of water table position with time calculated using this method. The response is heavily weighted toward the early time, which means that the pumping rate can probably be decreased fairly quickly from the higher initial values as well. The response is also very dependent on the effective porosity of the solidified mass.

The results shown in Figure 6-15 indicate that the time required to reduce the leachate storage within the landfill and establish steady state water table in the solidified mass is likely in the order of one to six years. In addition, there will be some initial period of time in which the change in hydraulic head in the underdrain layer (which occurs within days of turning on the pumps) will propagate through the solidified mass and begin to draw the water table down. This time period was estimated using the technique outlined by Wolff (1970). The compressibilities for clay of 1×10^{-8} to 1×10^{-6} sq. m/N

FIGURE 6-15 ESTIMATED RATE OF WATER TABLE DECLINE AT DRAIN PIPE OR SUMP MIDPOINT



was used to provide a conservative estimate. The results indicated that the hydraulic head change would propagate through the solidified mass in the order of several days to slightly greater than one year, depending on the solidified mass compressibility.

6.5.4 Conclusions

It is important to recognize that the results presented here should be treated only as guidelines from the purpose of comparing the alternate underdrain designs. To very accurately model the performance of the underdrain systems would require the use of a transient, fully three-dimensional ground water flow model. While these are available, the associated costs and time requirements are not considered to be beneficial at the conceptual design stage.

Based on steady state analyses, it appears that sumps (Alternative 1) should be spaced at a maximum of about 140 m from each other, and no more than about 70 m from the edge of the landfill. A pumping capacity of about three times the long-term maximum infiltration rate of 0.3 m/year per unit landfill area will be required initially to reduce the leachate storage in the landfill while meeting the minimum performance standard within days of turning on the pumps. The pumping rate can be decreased with time according to field performance monitoring.

Drain pipes, on the other hand, can be spaced at greater than 300 m apart, therefore perimeter drains (Alternative 2) appear to be feasible on this basis as do underdrain pipe networks (Alternative 3). However, closer drain pipe spacing, in the order of 150 m, and an initial pumping capacity in the order of 1.2 m/year per unit landfill area, will be required if the minimum performance standard must be met within days of initiating pumping.

Steady state water table conditions will likely be achieved in the landfill within a total period of one to seven years depending on the effective porosity and compressibility of the solidified mass. However, the drawdown is greatest during the early time, therefore the required pumping rate is expected to decrease fairly rapidly.

The drain pipe spacing (over the ranges studied) was found to be relatively insensitive to the hydraulic conductivity of the overlying solidified mass, moderately sensitive to the head maintained in the drain pipes and to the cover infiltration rate, and very sensitive to the drain layer thickness and the hydraulic conductivity of the underdrain layer material. These relationships provide an understanding of the consequences that can be expected should various components of the design not meet specifications or fail.

A very important related issue is the use of very low permeability cover materials such as synthetic membranes. These have the potential to reduce infiltration substantially under active operating conditions, which means that total leachate collection and treatment quantities are also substantially reduced. However, the preferred operational mode for the landfill is passive, in which case the synthetic membrane in the cover provides no significant benefit for the shallow entombed concept, and in fact may be subject to years of decay prior to being required (if at all). Therefore, an appropriate strategy to consider is to install a synthetic membrane in the cover only if and when the active operational mode is required as a contingency. This may be practical since it would only require construction work at the landfill surface.

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APPENDIX A: SOFTWARE FACT SHEET - "AQUIFER"

SOFTWARE NAME: AQUIFER

AUTHOR: E. Frind
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COMPUTER SYSTEM/LANGUAGE: IBM 4341/Fortran
HP9816/Basic 2.0

GENERAL DESCRIPTION:

This program is a quasi-three dimensional finite element model for determining transient or steady state areal flow regimes in a anisotropic, heterogeneous saturated subsurface. The aquifer can be confined, unconfined or leaky.

ASSUMPTIONS:

- flow is governed by the Laplace equation for steady state conditions and by

$$\frac{\partial}{\partial x}\left[T \frac{\partial \phi}{\partial x} \right] + \frac{\partial}{\partial y}\left[T \frac{\partial \phi}{\partial y} \right] + N(x,y,t) = S \frac{\partial \phi}{\partial t}$$

  for transient conditions where

  T = transmissivity [L^2/T]
  N = areal recharge flux [L/T]
  S = storativity [dimensionaless]
  ϕ = hydraulic head [L]

- water table remains constant
- no water contribution from the aquitard storage

Aquifer

- Horizontal flow
- Uniform thickness and constant
- Fully saturated medium
- Grains are rigid

Fluid

- Incompressible
- Isothermal

Wells

- Wells appear as nodal point source/sinks
- Not representative near well

INPUT PARAMETERS:

- Background information (Job name, etc.)

Finite element data
- node coordinates
- element incidences

Nodal properties
- hydraulic conductivities
- initial conditions
- specific yield
- aquifer/aquitard thickness

Boundary conditions
- constant head
- constant flux

OUTPUT:

- Head or pressure at nodal points verses time
- Graphical presentation of data
- Hardcopy output of data

SETUP TIME: Approximately one minute to load the systems and the program. Typically half minute to retrieve a data file from a disk or ten to twenty minutes to input data from keyboard.

RUN TIME: Interactive, the average time per plot is dependent on size of the problem.

REFERENCE:

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University of Waterloo